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NONDESTRUCTIVE EVALUATION (NDE) EXPLORATORY DEVELOPMENT FOR AIR FORCE SYSTEMS

Delivery Order 0006: Paint Stripping Effects on Fluorescent Penetrant Inspection

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Universal Technology Corporation

DECEMBER 2009
Final Report

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14. ABSTRACT

Paint removal is required before conducting fluorescent penetrant inspection (FPI). The effects of various pre-inspection paint-removal processes on FPI indications of fatigue cracks were evaluated using 2024-T3 and 7075-T6 aluminum specimens. Comparative data was obtained by conducting FPI of the specimens before painting and after paint removal. Nearly all the FPI indications were adversely affected by plastic media blasting. Over 70 percent of the FPI indications of cracks in specimens cleaned with chemical stripper were also adversely affected. Atmospheric plasma was the media least detrimental to the production FPI indications, but additional evaluation of this method is required. Pre-paint and post-strip corollary measurements of eddy current responses from the cracks and of bulk and superficial hardness of stripped surfaces were made. Eddy current signals maintained sufficient amplitudes for reliable crack detection. Minor changes in hardness occurred.

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Table of Contents

Table of Contents (Concluded)

List of Figures

List of Tables

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J. Edward Porter, Universal Technology Corporation – Conducted all fluorescent penetrant inspections (FPI) of cracked specimens, measured and recorded the brightness data for FPI indications, provided digital photographs of all crack indications, and archived the digital data.

Nicholas Heider, AFRL/RXSA – Recorded optical-microscope images of all cracks prior to painting. Measured the crack lengths from the microscope images.

Adam Long, University of Dayton Research Institute – Mounted and polished blank specimens of 2024-T3 and 7075-T6 prior to painting; sectioned and polished specimens after paint-stripping. Provided scanning-electron-microscope (SEM) images of some cracks.

Clay Baldwin, University of Dayton Research Institute – Painted all specimens and monitored accelerated curing of the paint. Removed paint from designated specimens with two types of plastic media and a chemical stripper.

Peter Yancey and John Waldrup, AP Solutions – Applied the company's cold atmospheric air plasma process (PlasmaFlux™) to remove paint from designated specimens.

Robert Ware, AFRL/RXSA – Provided SEM images of specimens after paint removal and interpretation thereof. Provided SEM spectrographic data to identify foreign material in or around some cracks.

M. H. Jubara, Chemsys Incorporated – Conducted microscope-based Fourier Transform Infrared spectrometry and X-Ray Fluorescence.

David Roberts, Universal Technology Corporation – Obtained and documented hardness measurements of cracked specimens before painting and after paint-stripping.

Daniel Laufersweiler, Universal Technology Corporation – Obtained and documented eddy-current crack indications before painting and after paint-stripping. Provided technical and editorial reviews of this report.

John C. Brausch, AFRL/RXSA -- Provided technical and editorial reviews of this report.

1. SUMMARY

A fatigue crack was grown in each of twenty-six aluminum specimens evenly divided between two alloys, 7075-T6 and 2024-T3. Fluorescent penetrant inspection (FPI) was conducted on the specimens and indication-brightness data were recorded for all cracks. Three other types of measurements were also made on the specimens: eddy current response from each crack, bulk hardness and superficial hardness. A small area, approximately 0.2-inch square, encompassing each crack was masked to prevent foreign material from entering the cracks during the subsequent painting process consisting of alodine, primer paint, top-coat paint, room-temperature paint cure, and accelerated paint aging in an oven. After the specimens were returned to room temperature, the masking over the cracks was removed. Specimens of each alloy were split into four groups, and the paint was removed from each group by one of the following methods: Type II plastic media blasting, Type V plastic media blasting, chemical stripper, and atmospheric plasma. FPI was repeated and indication-brightness data were again recorded for all cracks. The eddy current and hardness measurements were also repeated and recorded.

Eighty-five percent of all FPI indications were adversely affected by the paint removal process, i.e., the indications retained less than 100 percent of their pre-paint brightness. The only paint-stripping process for which all of the specimens had detectable post-strip indications was plasma, although not all indications retained 100 percent of their pre-paint brightness. Specimens in the 7075-T6 plasma group were the only ones of that alloy to have easily detectable post-strip indications, and three of the four 2024-T3 specimens in the plasma group had indications brighter than the pre-paint indications.

Microscopic examination of specimens stripped with Type II and Type V plastic media provided evidence of metal upset/peening on specimen surfaces due to media impingement, media embedded in cracks and reduced crack-openings, all of which correlated with the significant reductions in FPI indication brightnesses. In addition, an obvious semi-transparent coating was detected on specimens treated with Type V plastic media. Although the chemical-strip process did not cause any metal upset, it left residues of stripper and dissolved paint in cracks that degraded FPI indications.

Microscopic examination of the specimens stripped with plasma produced some unique findings, all related to the process, but none of which severely affected the FPI crack indications: 1) irregular spots that looked as if the aluminum had eroded away, 2) circular spots that looked like pools of melted aluminum that had re-solidified, and 3) shiny, black deposits that had the appearance molten material splattered onto the treated surfaces. Consultation with the vendor of the plasma-strip process revealed that arc strikes can produce localized erosion as well as melting and re-solidification of aluminum, and erosion of the plasma nozzle can produce molten drops of copper that may be deposited on a specimen surface.

All cracks continued to produce eddy current signals of sufficient amplitude to make them still easily detectable after paint removal. All but one of the eddy current crack signals had less amplitude after paint removal than before paint was applied. The median decrease was 18 percent and the average decrease was 16 percent, indicating the lower percentage decreases were slightly dominant. Six of the decreases were six percent or less. Variability inherent in a manual eddy current inspection undoubtedly contributed to the signal changes.

The only noticeable effect that the paint removal process had on alloy hardness was for the bulk hardness of the 2024-T3 specimens stripped with plasma. Decreases in hardness of two to four points for those specimens indicate a need for further evaluation of the effects of the plasma paint-removal process.

2. INTRODUCTION

Fluorescent penetrant inspection (FPI) is used extensively in the United States Air Force (USAF) for both full-field and localized inspection of aircraft structural components to assess structural integrity at periodic depot maintenance intervals. Of specific concern is the inspection of aluminum wheels, which are typically coated with a primer and topcoat to protect the wheels from the environment and prevent corrosion. All coatings must be removed prior to performing FPI. The most common coating removal techniques are plastic media blasting (PMB) and chemical stripping. Previous studies by the United States Navy indicated that the use of Type II PMB on aluminum components can cause surface modification (peening), which clogs surface-breaking cracks and prevents their detection with FPI.

Implementation of less aggressive Type V PMB within USAF paint-stripping practices reportedly resulted in significantly less surface peening compared to Type II PMB. In addition, recent work under a Small Business Innovative Research (SBIR) Phase I study demonstrated the possibility of using atmospheric (cold) plasma (AP) as a very rapid method for striping organic coatings and sealants without harming metallic substrates. However, no studies had been conducted to evaluate the effects on FPI results of using either Type V PMB or AP.

In the USAF chemical stripper is also used to remove coatings, either by itself or in conjunction with PMB. Therefore, it was included with the other three media in this comparative study.

Plastic media and chemical paint removal was performed at the Air Force Research Laboratory Materials and Manufacturing Directorate, System Support Division, Materials Integrity Branch (AFRL/RXSA) at Wright-Patterson Air Force Base in Ohio. Plasma paint removal was performed by Atmospheric Plasma (AP) Solutions, Cary, NC.

3. TEST SPECIMENS

3.1 Cracked Specimens

Extruded aluminum bar stock of two alloys (2024-T3 and 7075-T6) were cut into flat-bar test specimens, 6 inches long by 1 inch wide by 0.25 inch thick. A low-cycle fatigue (LCF) crack was grown in the center of one of the broad surfaces of each specimen by applying three-point bending loads. The targeted range of crack lengths was 0.030 to 0.100 inch. The actual lengths, optically measured with a microscope, are tabulated in Table 1. The group assignments for specimens of each alloy were based upon the brightnesses of the pre-paint FPI indications; the objective was to have a similar distribution of brightness values in each group regardless of crack lengths.

Table 1. Lengths of Cracks in Test Specimens

Paint Removal Process	2024-T3		7075-T6	
	Specimen No.	Crack Length (mils or 10^{-3} inch)	Specimen No.	Crack Length (mils or 10^{-3} inch)
Type II Plastic Media Blasting (PMB-II)	601-01	94.0	609-04	26.8
	601-04	30.3	609-05	74.1
	601-06	87.6	609-07	52.5
Type V Plastic Media Blasting (PMB-V)	601-13	24.4	609-09	71.0
	601-15	53.6	609-13	64.0
	601-22	33.4	609-14	35.3
Chemical Stripper	601-16	63.1	609-01	72.9
	601-18	50.2	609-02	109.3
	601-19	63.1	609-03	24.1
			609-15	38.5
Atmospheric (Cold) Plasma	601-08	80.3	609-08	81.8
	601-10	46.2	609-10	110.7
	601-14	24.7	609-12	54.1
	601-21	51.0		

FPI was performed to evaluate the crack indications on the newly manufactured specimens. If an indication was nonexistent or very dim, a localized etch was performed until a recordable indication brightness was obtained. The etchant consisted of a standard sodium hydroxide solution in which sodium hydroxide pellets were dissolved at a concentration of 500 g per 100 mL of deionized water.

3.2 Specimen Blanks

Eight one-inch un-cracked squares of each alloy were metallurgically mounted and polished. One half of each square was masked with Compac #805 aluminum-foil tape with acrylic adhesive (MIL-T-23397B, Amendment 2, Type II). The service temperature range of the tape is -30°F (-34°C) to 325°F (163°C). All masked specimen blanks were processed with paint, and two each were processed with one of the paint-removal media along with the respective group of cracked specimens. Then the tape was removed for comparative examination of the treated and untreated surfaces.

4. FLUORESCENT PENETRANT INSPECTION

4.1 Overview

The FPI process consisted of pre-cleaning the specimens, processing the specimens with the penetrant system and developer, measuring the brightnesses of the crack indications, photographically documenting the indications, and post-cleaning the specimens. After it was established that the newly manufactured specimens had viable FPI crack indications, FPI was conducted three times. For each specimen the three indication brightness measurements were averaged, and that average was designated as the pre-paint brightness. After the painting and stripping operations were completed, FPI was conducted again. Along with the specimens, FPI was also conducted on a control group of five cracked specimens to monitor the repeatability of the FPI process. The control specimens were made of Inconel 718 and had history of providing consistent crack indications.

4.2 Cleaning

4.2.1 Equipment and Materials

- Custom rack for specimens (Figure 1).
- Acetone.
- Container to accommodate acetone and the custom rack with specimens.
- Ultrasonic cleaner, Lewis Model 1209-SH, with continuous ultrasonic output power of 800 watts RMS.
- Sink with warm running water.
- Parts-cleaning brush with soft fiber (no metal) bristles.
- Mild dishwashing soap.
- Container for dishwashing-soap and water solution.

4.2.2 Pre-Cleaning

- Place the specimens into the custom rack in serial number (S/N) sequence.
- Place the rack into the container with sufficient acetone to completely immerse the specimens, and put a cover on the container.
- Place the covered container into the ultrasonic cleaner filled with water according to the manufacturer's instructions.
- Turn on the ultrasonic cleaner for 5 minutes.
- Turn off the ultrasonic cleaner and allow the specimens to remain immersed in the solvent for an additional 10 minutes.
- Remove the holder with specimens from the solvent and place it in the recirculating oven at 135 ± 5°F (21 ± 3°C) for 30 ± 5 seconds to flash off any remaining acetone.
- Visually examine the specimens under both UV-A radiation and white light to verify that there is no residual fluorescent indication of any crack and the specimens are clean and dry.

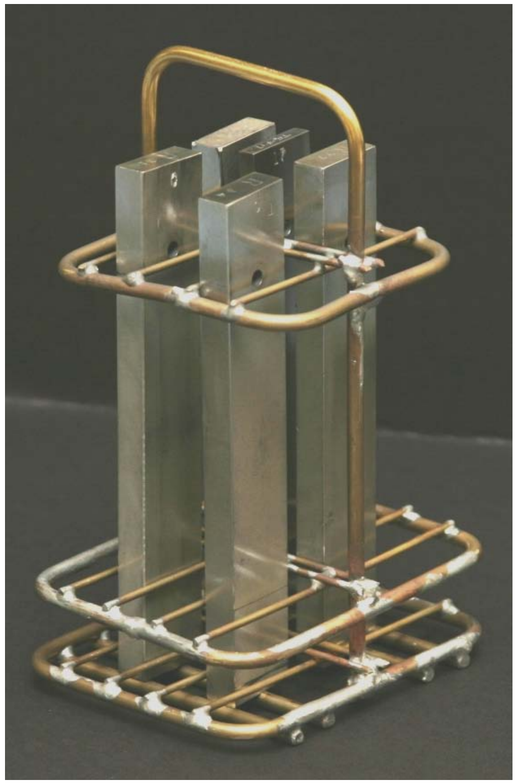


Figure 1. FPI Custom Specimen Rack

4.2.3 Post-Cleaning

- Transfer the specimens to the sink.
- In S/N sequence dip the first specimen into the soap-and-water solution.
- Dip the parts brush into the soap-and-water solution and brush the surfaces of the specimen to remove the developer. Brush the cracked surface parallel to the crack only.
- Rinse the specimen under warm running water and place it on end against a support on a workbench to drain.
- Repeat steps 2 through 4 for the remaining four specimens in sequence.
- Dry the first specimen with a clean, soft, dry paper towel and place the specimen into the rack. Repeat for the remaining four specimens in sequence.
- Place the rack into the container with sufficient acetone to completely immerse the specimens, and put a cover on the container.
- Place the covered container into the ultrasonic cleaner filled with water according to the manufacturer's instructions.
- Turn on the ultrasonic cleaner for 5 minutes.

4.3 Penetrant System and Developer

A Level 3, Method D, Type 1 penetrant system was selected for processing the cracked specimens: Met-L-Chek FP-95A(M) fluorescent liquid penetrant and E-58D hydrophilic emulsifier mixed at a 20% concentration. A dry powder developer, Magnaflux ZP-4B, was selected for this study because experience at AFRL/RXSA with sensitivity testing of penetrant materials in accordance with the SAE Aerospace Material Specification, AMS 2644, *Inspection Materials, Penetrant* has shown it to provide the most repeatable penetrant indications over multiple FPI cycles of LCF-crack specimens.

4.4 Penetrant System and Developer Processing Parameters

The variables of the penetrant inspection process were minimized by conducting the inspections using the tightly controlled processes developed for testing the sensitivity of candidate penetrant materials for inclusion on the SAE Qualified Products Database, QPD AMS 2644, *Inspection Materials, Penetrant*. Table 2 contains the penetrant system and developer processing parameters. Each step was closely timed, and the water and oven temperatures were closely monitored. For process control during critical steps, a group of five specimens were processed simultaneously as a set whenever possible. To maintain process control when it was necessary to process specimens individually (e.g., dipping into penetrant and applying developer), the specimens were always processed in the same sequence and the timer for the respective step was started after the last specimen was processed.

Table 2. Penetrant System and Developer Processing Parameters

Penetrant Dwell	Dip, drain for 30 minutes ± 10 seconds.
Prewash[1]	Method D: Spray for 30 ± 5 seconds with water.
Emulsification	Method D: Immerse for 2 minutes ± 5 seconds, no agitation.
Wash[1]	Method D: Spray for 1 minute ± 5 seconds with water. Remove dripping water: one light wipe with clean towel.
Dry[2]	5 minutes ± 10 seconds in oven.
Developer	Form a: dip, agitate, remove and tilt to let developer slide off specimen. Dwell for 5 minutes ± 10 seconds before measuring indication brightness.

[1]Water: 25 ± 2.5 psi (172 ± 17 kPa) and 70 ± 5°F (21 ± 3°C)
[2]Oven: 135 ± 5°F (21 ± 3°C)

Figure 2 shows the custom wash apparatus used to simultaneously wash the five specimens in a group. Wash time is controlled by opening and closing a quarter-turn ball valve in the supply line. Figure 3 shows a close-up of the wash-apparatus fixture with the removable holder for transferring specimens to and from the container with hydrophilic emulsifier. After the wash following emulsification, specimens are transferred back to the custom rack (Figure 1) for drying.

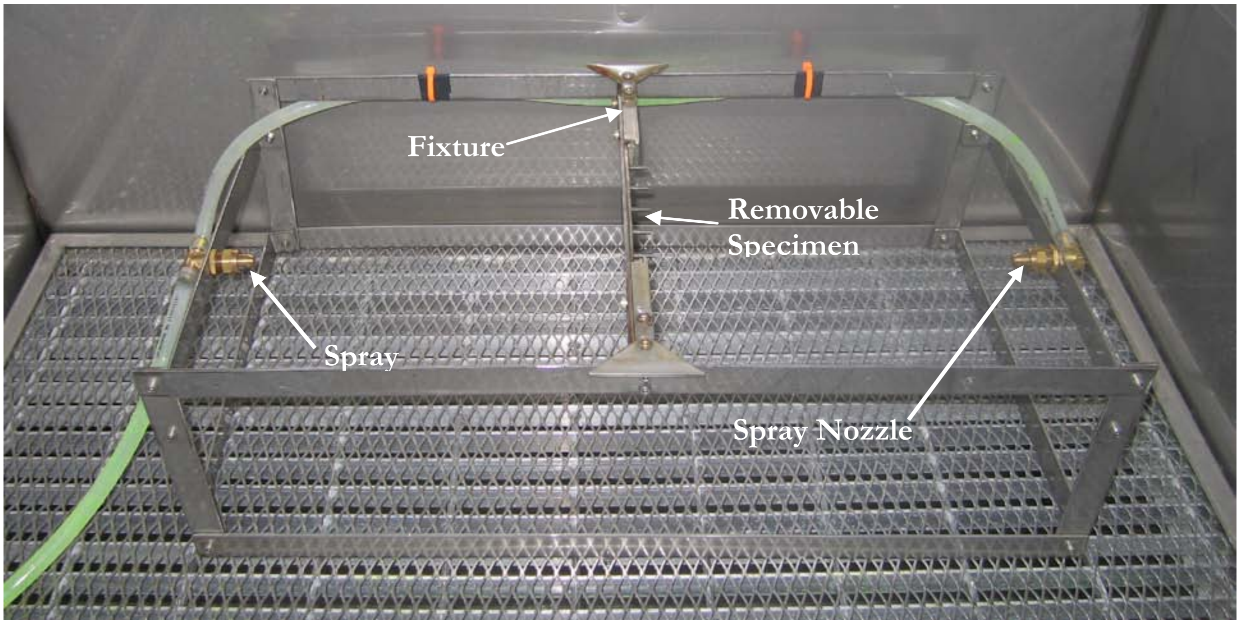


Figure 2. FPI Wash Apparatus

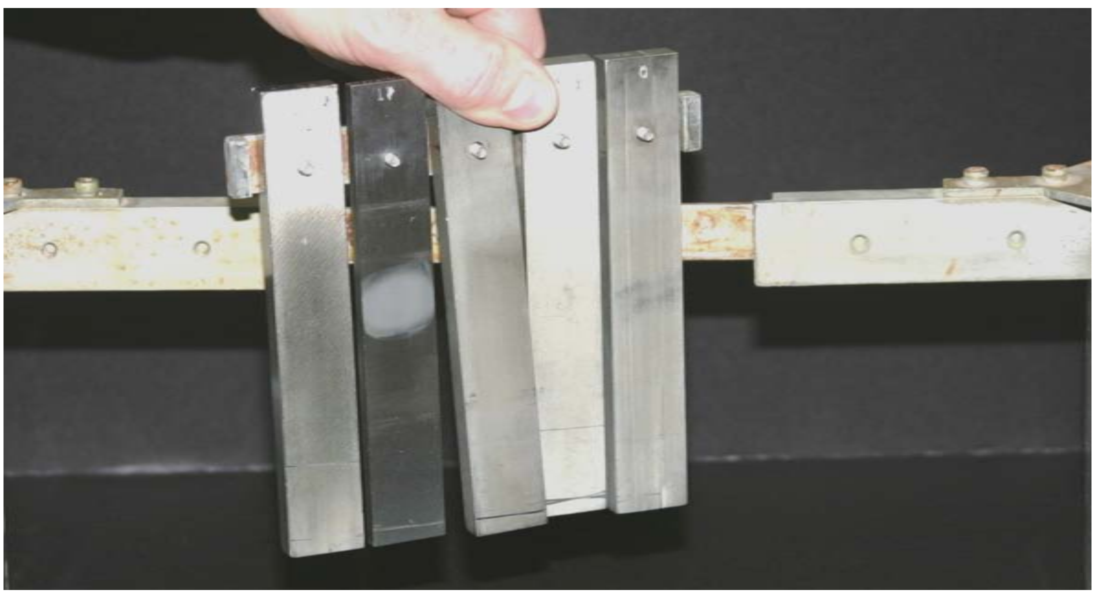


Figure 3. FPI Wash-Fixture Removable Holder for Fatigue-Crack Specimens

4.5 Brightness Measurement of Penetrant Indications

A photometer, Photo Research Model PR-1500 Spotmeter® with a ¼-degree aperture and an MS-55 macro lens, was used to measure the brightness of the penetrant indications. An internal photopic filter was used to simulate the response of a typical human eye. The configuration of the measurement station is shown in Figure 4. With this setup the field of view at the specimen surface was approximately 0.060 by 0.020 inch; the long axis of the elliptical area was aligned with the crack indication being measured. The UV-A intensity at the specimen surface was 2200-2400 $\mu W/cm^2$.

Before each group measurement sequence the intensity of the UV-A light was checked with a radiometer, and the self-calibration of the Spotmeter® was accomplished. UV-A lamp tubes were cleaned or replaced as necessary to maintain consistent intensity.

In the same sequence followed during penetrant processing one specimen at a time was placed on the movable stage mounted to the jack stand, and the stage was adjusted to place the indication within the field of view of the photometer. The value of the indication brightness displayed on the Spotmeter® digital display was recorded after subtracting the brightness of the fluorescent background adjacent to the crack, which was measured by moving the crack indication out of the field of view of the photometer.

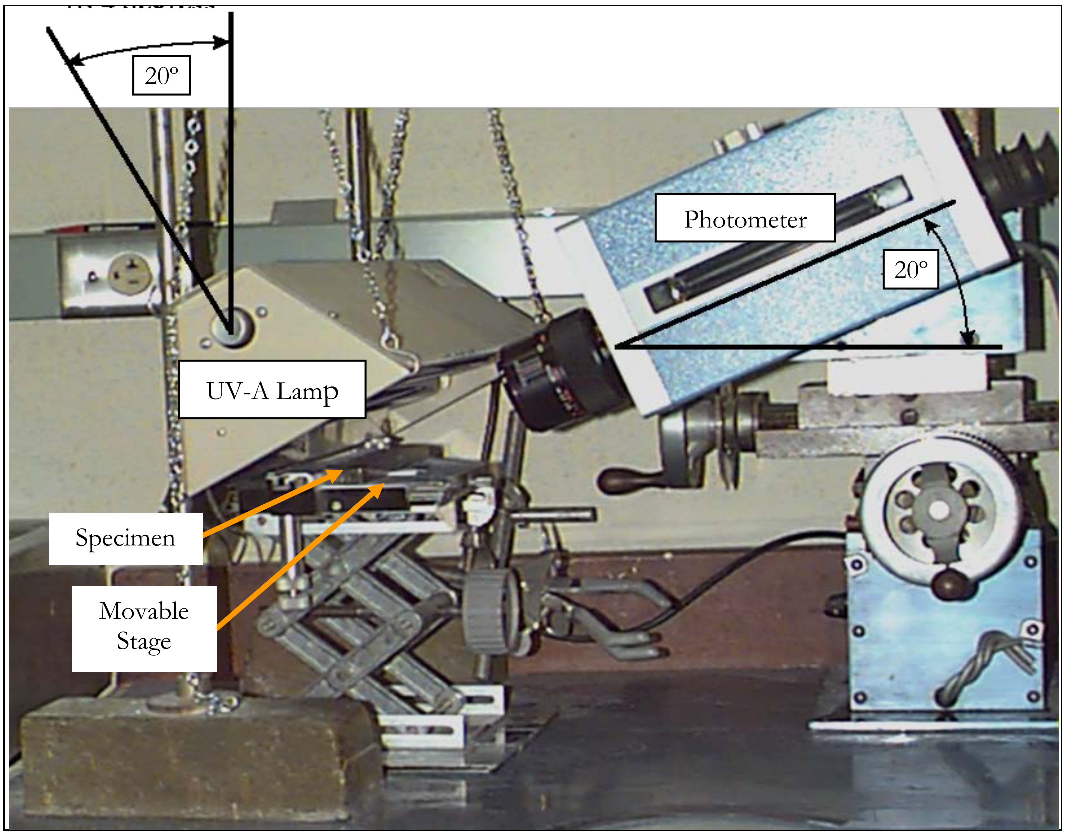


Figure 4. Equipment Configuration for Measuring Brightness of Crack Indications

5. EDDY CURRENT INSPECTION

Eddy current responses were obtained from each crack before any surface treatment was applied to the specimens and again after the paint was removed.

5.1 Equipment

The equipment was set up according to USAF T.O. 33B-1-2 WP 402 00, *Technical Procedures Eddy Current, Surface, Aluminum, Weakly Ferromagnetic and Nonferromagnetic Alloys*. The equipment used was as follows:

- Instrument -- Nortec 2000D.
- Probe -- Nortec P/100kHz-500kHz/AS50910.
- Probe holder -- to keep probe perpendicular to surface.
- Reference standard -- USAF Eddy Current General Purpose Standard Aluminum.

5.2 Calibration

The equipment was calibrated by setting the null point at 10 percent of full screen height (FSH) on the instrument display and the vertical signal from the 0.020-inch deep notch on the reference standard at 80 percent of FSH. The instrument vertical and horizontal gain settings were recorded.

5.3 Inspection Procedure

- Probe was placed on the surface of a cracked specimen and instrument was nulled.
- Probe was manually scanned over the crack location and paused when a signal was detected.
- Probe was moved slowly in all directions and stopped when signal peaked.
- The above three steps were repeated to verify the peak amplitude.
- Amplitude of peak signal was recorded.
- If the peak amplitude was above 80 percent FSH, the instrument vertical gain was decreased until peak signal equaled 80 percent FSH, and that gain setting was recorded.
- The vertical gain was returned to calibration setting, and the 80-percent signal from the 0.020-inch slot on the reference standard was verified.
- The procedure was repeated for all the cracked specimens.
- After the paint was removed, the procedure was repeated. The equipment was nulled on the specimens with the probe in contact with the center area that had been masked during the painting process.

6. HARDNESS MEASUREMENTS

Before any paint was applied bulk hardness and superficial hardness measurements were made on each specimen with a Wilson Instruments 2000T load-cell controlled Rockwell hardness tester. Three measurements of each type were made across each specimen one inch away from the crack, bulk measurements to one side and superficial measurements to the other, as indicated by the two sets of dots in Figure 5. The three measurements of each type were averaged. After paint was removed the measurements were repeated a short distance away from the original spots and changes in the averages were calculated.

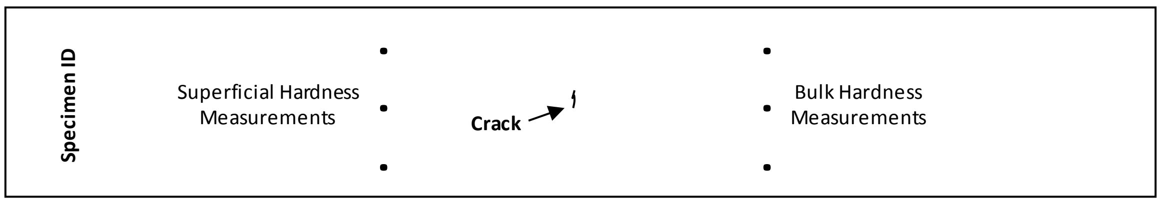


Figure 5. Location of Hardness Measurements

7. PHYSICAL AND ANALYTICAL EXAMINATION OF SPECIMENS

7.1 Microscopic Examination

After viable FPI indications were obtained for all specimens, optical microscope examination was conducted to measure the lengths of the cracks. Digital images were recorded for all cracks.

Following paint removal representative specimens from each paint-removal group of each alloy were examined with an optical and/or a scanning electron microscope (SEM). Efforts were made to correlate post-strip FPI results with evidence of surface deformation or foreign material inside the cracks. When possible, energy dispersive spectrometry (EDS) on the SEM was conducted to analyze material inside cracks.

The specimen blanks were examined with an optical microscope to compare the polished and treated surfaces. One blank from each media-treatment group was sectioned, mounted and polished for cross-sectional microscopic examination. Of particular interest was the detection of any distinct layer of material coating the treated surfaces.

7.2 Microscope-Based Fourier Transform Infrared Spectrometry (μFTIR)

Surfaces of the treated specimen blanks were analyzed to determine the composition of any residual coating. Scrapings were separately collected from both the polished and treated sides of a specimen. Specimens treated with PMB-I, PMB-V and chemical stripper were analyzed.

7.3 X-ray Fluorescence (XRF)

A semi-quantitative analysis was conducted for elements present at both the polished and treated surfaces of each blank specimen. Estimates of the relative concentrations (in weight percent) of the detected elements were obtained by a standardless quantification routine. The estimate did not take into account the possible presence of XRF non-detectable elements (atomic number 11 and below).

8. APPLICATION OF PAINT

All paint was applied by University of Dayton Research Institute personnel at the Coatings Technology Integration Office (CTIO). Organizationally, CTIO is part of the AFRL/RXS Logistics Systems Support Branch; its organizational symbol is AFRL/RXSSO.

8.1 Crack Masking

The ideal (real-life) situation would have had fatigue cracks grown in specimens that were already painted. Since that was not feasible for this study, precautions were taken to prevent any contamination from entering the cracks during the painting process. A 3/16-inch square of aluminum foil was adhered to the center of a slightly larger piece of the Compac #805 aluminum-foil tape aluminum tape, which was then centered over each crack and adhered to the respective specimen.

8.2 Alodine Chemical Conversion Coating

Before paint was applied specimens were pretreated with Alodine 1600, a chrome conversion coating, using the following standard CTIO process.

1. Scrub with a maroon Scotch-Brite™ pad and a 10:1 mix of tap water/Brulin detergent.
2. Rinse with tap water and verify specimen to be water break free. Immerse in deionized water until additional specimens to fill the dip rack were prepared.
3. Immerse each rack of specimens for 5-minutes in a circulating bath of a 10:1 mix of tap water/Brulin detergent heated to 140º F.
4. Perform a two-stage rinse.
    a. Dunk in tap water ten times without aeration.
    b. Spray with low-pressure deionized water.
5. Immerse in a circulating de-oxidizing bath for two minutes.
6. Perform a two-stage rinse.
    a. Dunk in tap water ten times with aeration.
    b. Spray with low-pressure deionized water.
7. Immerse in a circulating bath of Alodine 1600 to provide chrome uptake on the specimens at the rate of 45-50 mg/ft^2 (one minute for these specimens).
8. Perform a two-stage rinse.
    a. Dunk in deionized water ten times with aeration.
    b. Spray with low-pressure deionized water.
9. Dry at ambient conditions overnight.

8.3 Primer Coat of Paint

Specimens were primed with PPG CA7233 according to manufacturer's directions. The primer is qualified to MIL-PRF-23377. All specimens were primed together as a group. The coating thickness was 0.0008 inch.

8.4 Top Coat of Paint

A PPG CA9314grey topcoat, qualified to MIL-PRF-85285, was applied to the specimens according to manufacturer's directions. All specimens were primed together as a group. The coating thickness was 0.002 inch.

8.5 Paint Cure

The painted panels were allowed to cure at room temperature for 14 days. Then the specimens were placed in an oven for 96 hours of accelerated aging at 210° F.

8.6 Mask Removal

All tape and aluminum foil covering the cracks were removed from the specimens prior to paint removal.

9. PAINT REMOVAL

9.1 Type II Plastic Media Blasting

US Technology Corporation Polyplus® Plastic Blast Abrasive (Type II), grit size 10/20 was used to remove paint from one specimen at a time. The primary chemical ingredient of the media is polymerized urea formaldehyde. The product is qualified to MIL-P-85891(A).

9.2 Type V Plastic Media Blasting

US Technology Corporation POLY V® Plastic Blast Abrasive (Type V) was used to remove paint from one specimen at a time. The media is composed primarily of an acrylic polymer with a trace amount of methyl methacrylate.

9.3 Chemical Strip

CEE BEE A235 chemical stripper was used. Because this stripper has low viscosity, the seven specimens to be stripped were covered with a lint free cloth, which was then saturated with the A235. After the coating was loosened to the point of removal, the specimens were rinsed with warm tap water, final rinsed with deionized water and allowed to air dry at ambient temperature.

9.4 Cold Atmospheric Pressure Air Plasma

AP Solutions used its PlasmaFlux™ system to remove paint from specimens provided. The system uses a low pressure compressed air source and electricity to produce a special form of cold atmospheric-pressure air plasma that has the high chemical activity but without the intense heat of thermal plasma. The cold plasma attacks the polymeric component in paints and other coating systems. The PlasmaFlux™ process converts a portion of the removed paint into harmless gasses such as water vapor and carbon dioxide, leaving behind pigments and fillers that can be safely vacuumed away. The two main components of the PlasmaFlux™ system is the power supply, which provides the electrical signal to excite the air into the plasma state, and the "applicator" or hand-held nozzle/electrode that forms and shapes the plasma air stream.

For the specimens in this study the nozzle/electrode was attached to an automated scanner and a paint-removal technique was empirically developed to achieve the appropriate power level, plasma air-stream shape, scan speed and applicator height above a specimen. Once the technique was developed, it was applied to one specimen at a time.

10. RESULTS AND DISCUSSION

10.1 Fluorescent Penetrant Inspection

Eighty-five percent of all FPI indications were adversely affected by the paint removal process, i.e., the indications retained less than 100 percent of their pre-paint brightness. Only in the groups stripped with plasma did all specimens exhibit easily detectable post-strip indications. In fact, specimens in the 7075-T6 plasma group were the only ones of that alloy to have easily detectable post-strip indications. For specimens in the 2024-T3 plasma group three of the four indications were brighter than the pre-paint indications. Figure 6 charts the brightnesses of FPI indications measured after paint was stripped (post-strip) expressed as percentages of measurements made before the alodine and paint were applied (pre-paint). FPI data and pictures of indications are presented in Figure A- 1 through Figure A-10.

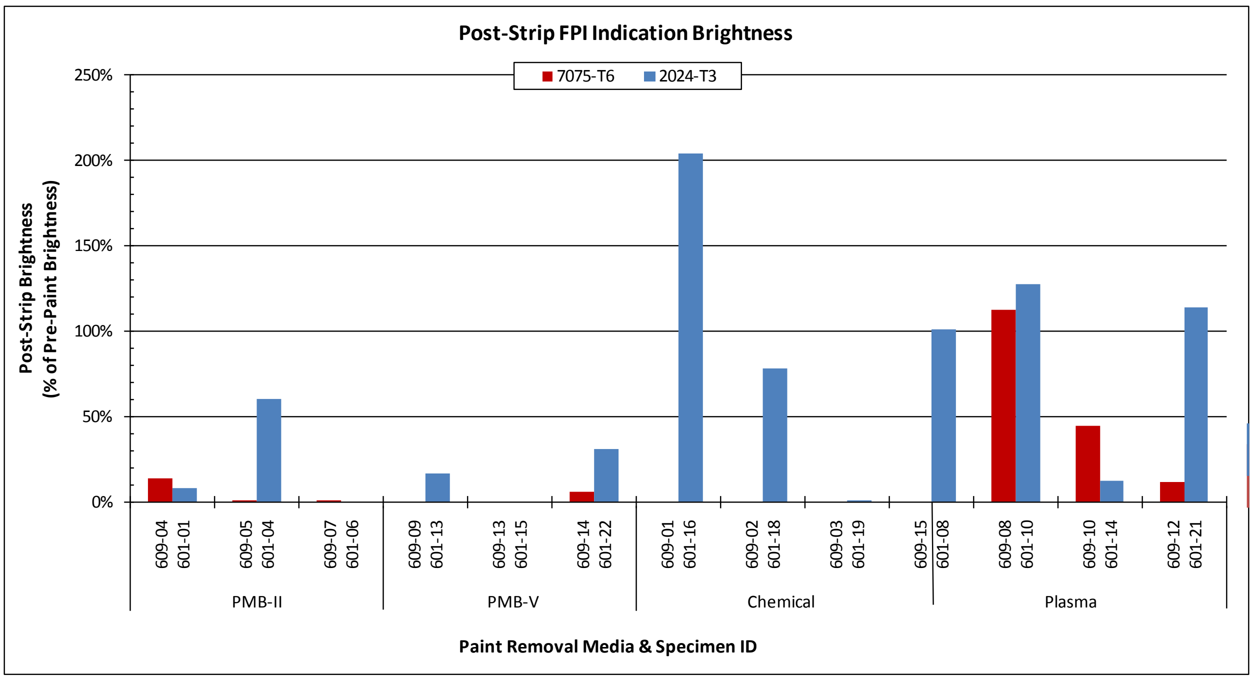


Figure 6. Post-Strip Brightness of FPI Crack Indications Compared to Pre-Paint Brightness

Broken down by alloy, 92 percent of the indications on 7075-T6 specimens and 69 percent of the indications on 2024-T3 specimens were adversely affected. This difference may be because the average pre-paint indication brightness of the specimens 2024-T3 was nearly twice the pre-paint average for 7075-T6. The average crack length in 2024-T3 was only slightly more than in 7075-T6.

Most surprising was the adverse effect that chemical stripping had on most FPI indications due to residues of paint and stripper clogging of the cracks as discussed in Section 10.6.3. The exception was the large percentage increase in indication brightness for 2024-T3 specimen 601-16, which could have been due to the crack opening up during the ultrasonic pre-cleaning during FPI.

The post-strip indication on 7075-T6 specimen 609-04 stripped with PMB-II was not "easily" detectable even though it retained a slightly higher percentage of its pre-paint brightness than did 7075-T6 specimen 609-12 stripped with plasma. The reason for this situation may become clear by referring to Figure A- 1, Figure A-2 and Figure A-5. The crack in 609-04 had approximately half the length and one-third the pre-paint indication brightness of the crack in 609-12. Retaining only a slightly higher percentage of a dimmer indication resulted in a relatively dim post-paint indication for 609-04. In addition, although the 609-12 post-strip indication was shorter, it was brighter than the 609-04 post-strip indication and therefore more easily detectable.

It should be noted that the pictures of FPI crack indications shown in the Appendix were taken with a 100 mm macro camera lens in a laboratory environment with high-intensity UV-A radiation (4600-4800 μW/cm^2). Therefore, although small and/or dim indications (e.g., 609-04) are visible in the pictures, they would probably not be visible during FPI inspection in a typical maintenance facility.

The low pre-paint indication brightness of less than 4 foot-lamberts (fL) for the relatively large crack (94 mils) in 601-01 is not unusual. The phenomenon is illustrated in Figure A- 1, where the crack lengths that are plotted along with the FPI data show little correlation to either the pre-paint brightnesses of the FPI indications or the effects of the paint removal processes. Conversely, the bright pre-paint indication (71 fL) for the 24-mil crack in 7075-T6 specimen 609-03 is more of an exception (Figure A- 6). However, the indication shown in Figure A-4c is 110 mils long, a discrepancy that remains unresolved.

10.2 Eddy Current Measurements

All cracks produced post-strip signals of sufficient amplitude to make them continue to be easily detectable. The average of the ratios of post-strip to pre-paint signal amplitudes was 84 percent while the median was 82 percent. Variability inherent in a manual eddy current inspection undoubtedly contributed to the signal changes, but the trend of lower post-strip signals indicates a systematic error possibly arising from a failure to precisely duplicate the pre-paint calibration for the post-strip inspection. Figure 7 presents the amplitudes of eddy current crack signals measured after paint was stripped expressed as percentages of pre-paint measurements. The amplitude data is presented in Figure A-11 and Figure A-12.

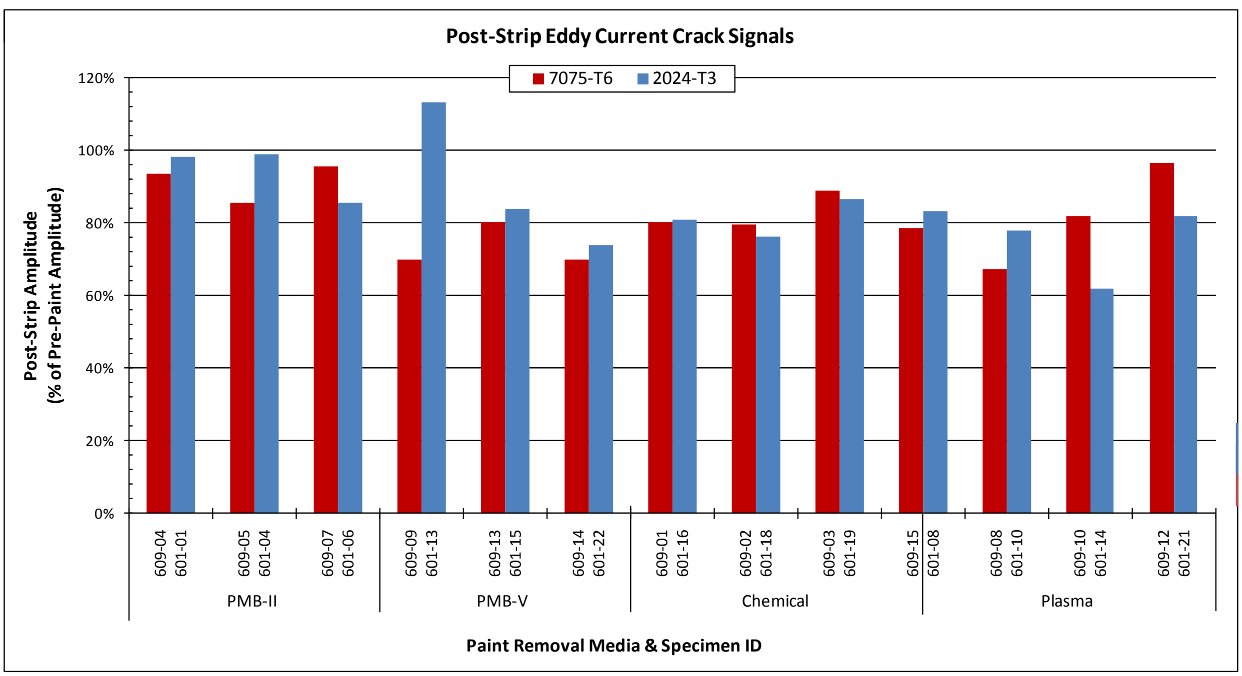


Figure 7. Post-Strip Eddy Current Crack Signals Compared to Pre-Paint Signals

The largest changes in crack signals were a positive 13 percent for 601-13 and a negative 38 percent for 601-14. Those very small cracks (approximately 24 mils) produced low-amplitude pre-paint signals (fine and ten percent FSH respectively), so small changes in amplitude produced high percentage changes.

The decreases in eddy current signal amplitudes ranged from one percent (601-04) to 38 percent (601-14). The PMB-II groups had the lowest average decrease, eight percent for 7075-T6 and six percent for 2024-T3. The largest average decrease for 7075-T6 was 27 percent for the PMB-V group. The average decrease for the 2024-T3 PMB-V group was 21 percent, discounting the increase for 601-13. The largest average decrease for 2024-T3 was 26 percent for the plasma group.

Changes in the amplitudes of cracks in specimens treated with chemical stripper were not anticipated. Clogging of the cracks with non-metallic material should not affect eddy current signals. Perhaps, this is more evidence indicating a calibration issue.

10.3 Hardness Measurements

10.3.1 Bulk Hardness

The changes in bulk hardness measurements were minor, usually falling within measurement variability. The exceptions were the slightly larger decreases for 2024-T3 specimens stripped with plasma. The post-strip hardnesses for specimens experiencing the largest decreases (601-08 and 601-10) were still over 13 points above the required minimum of 67 HRB. However, a decrease of this magnitude is of concern because it approaches the five percent limit imposed by material specifications on decreases caused by physical processing of a material.

The chart in Figure 8 presents the bulk hardness measurements made after paint was stripped expressed as percentages of pre-paint measurements. Figure A-13 and Figure A-14 contain the actual bulk hardness data and the specified minimum values for each alloy.

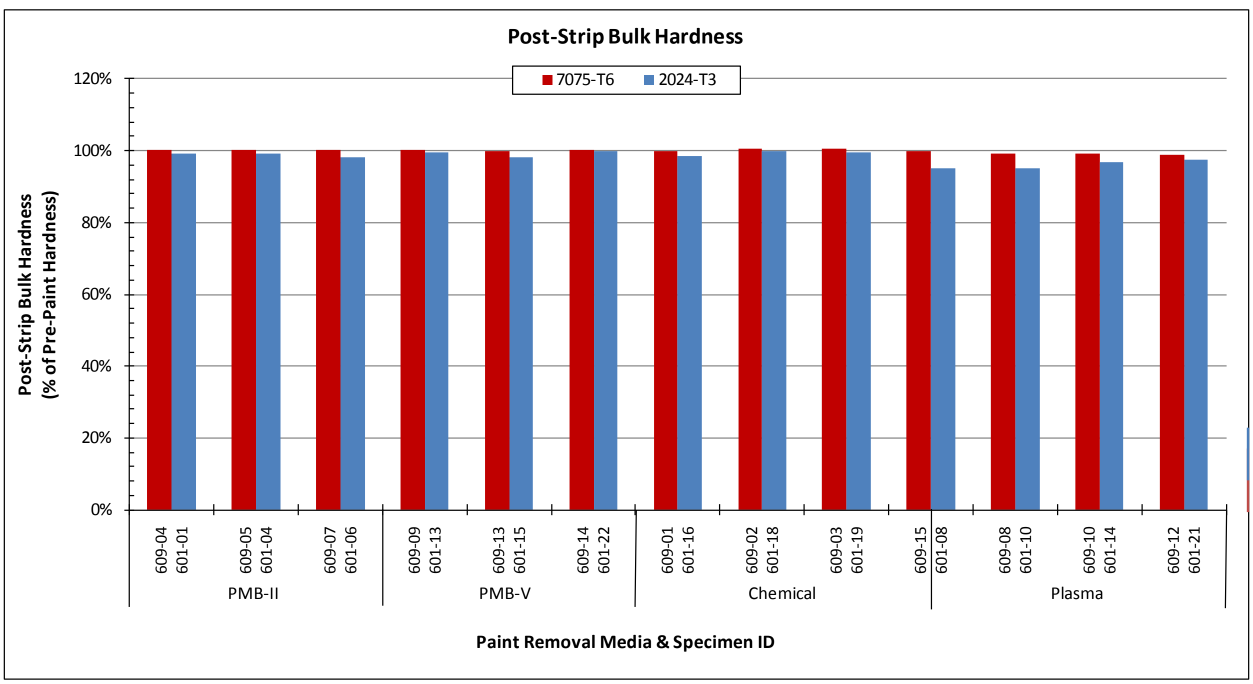


Figure 8. Post-Strip Bulk-Hardness Compared to Pre-Paint Hardness

10.3.2 Superficial Hardness

The changes in superficial hardness measurements were insignificant and fall within measurement variability. The pattern of lower post-strip measurements for the 2024-T3 plasma group is similar to that noted for bulk hardness, but the decreases in superficial hardness are smaller.

Figure 9 shows percentage changes between superficial hardness measurements made after paint was stripped expressed as percentages of pre-paint measurements. The actual bulk hardness data and the specified minimum values for each alloy are contained in Figure A-15 and Figure A-16.

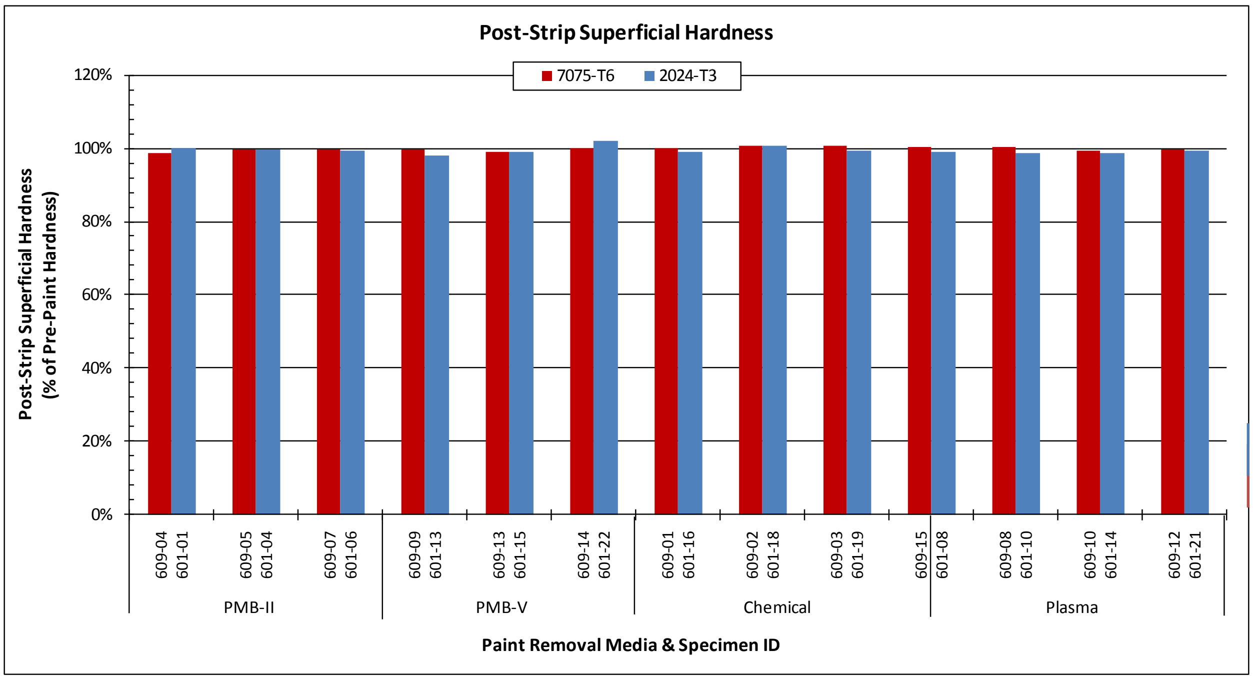


Figure 9. Post-Strip Superficial-Hardness Compared to Pre-Paint Hardness

10.4 Visual Examination

Simple visual observation revealed an obvious difference between the specimens stripped with the two types of plastic media. A semi-transparent coating covered the stripped areas of specimens treated with PMB-V (Figure 10). The square areas (containing the cracks) in the center of the specimens, which had been protected by tape during painting, are partially hidden by the residual media coating. On the other hand, the untreated square areas on specimens treated with PMB-II (Figure 11) are readily apparent. The figures show only 2024-T3 specimens, but the 7075-T6 specimens looked the same. The splotchy appearance of the specimens treated with PMB-II is due to non-uniform removal of the alodine conversion coating, an inconsequential side-effect of the paint stripping process.

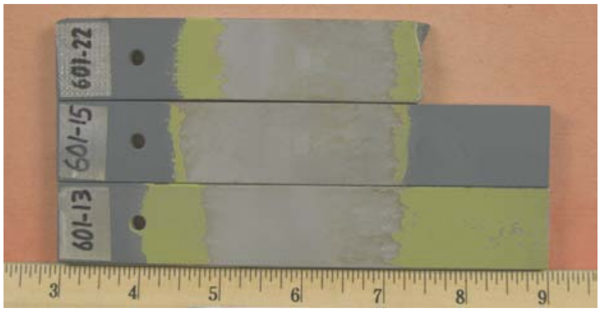


Figure 10. Specimens Stripped with PMB-V

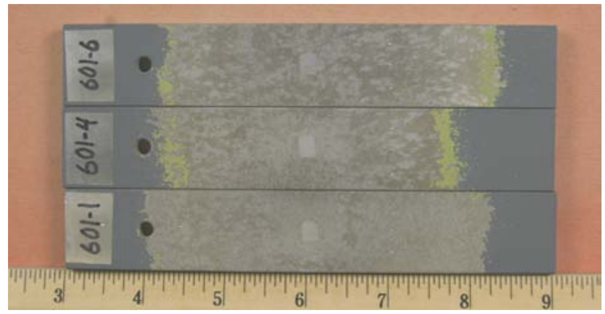


Figure 11. Specimens Stripped with PMB-II

On specimens stripped with chemical stripper there was no evidence of anything on the surface that would affect the formation of FPI crack indications (Figure 12 and Figure 13). Unlike the PMB and plasma processes the chemical stripper was applied to the entire area of all specimens. Only random spots of paint remained. In a typical USAF maintenance arena such residual spots of paint would be removed with some type of PMB, which could add to the problem of degraded FPI indications.

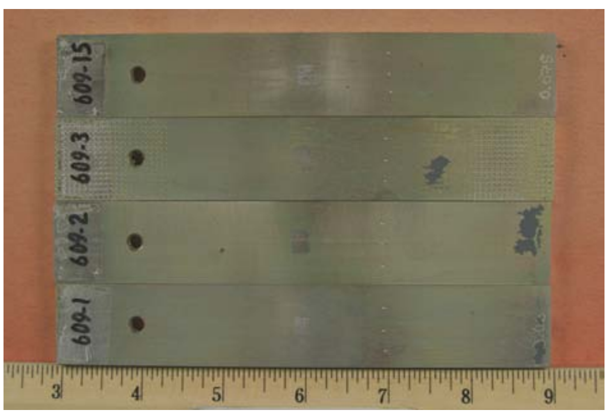


Figure 12. 7075-T6 Specimens Processed with Chemical Stripper

Figure 13. 2024-T3 Specimens Processed with Chemical Stripper

To the unaided eye nothing unusual was noted on the specimens stripped with plasma (Figure 14 and Figure 15) except for some transverse bands toward each end of 2024-T3 specimen 601-14, pictured at the top of Figure 15. The company (AP Solutions) that had removed paint with atmospheric plasma had used these areas (away from the center cracked area) to empirically develop the stripping parameters for these specimens. Consequentially, over-aggressive paint removal occurred in these areas before the parameters were optimized. When a hand-held 10X magnifier was used to examine these bands more closely, numerous tiny dark and bright spots were observed over the entire stripped surface. Similar features were also observed on the surfaces of the other six specimens. A close-up photograph of the center of specimen 601-14 (Figure 16) shows these features, which became the targets of subsequent microscopic examination as discussed Section 10.6.4.

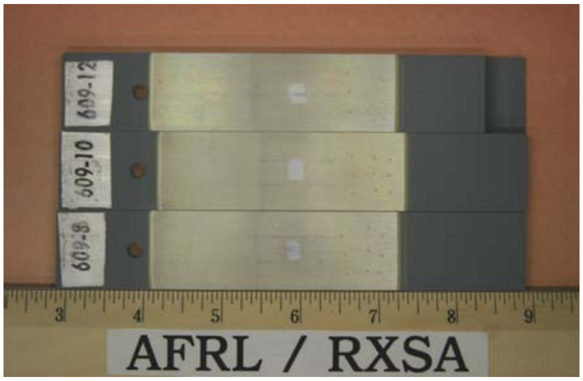


Figure 14. 7075-T6 Specimens Processed with Plasma

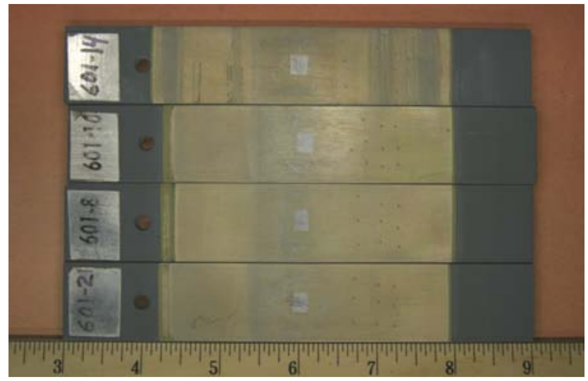


Figure 15. 2024-T3 Specimens Processed with Plasma

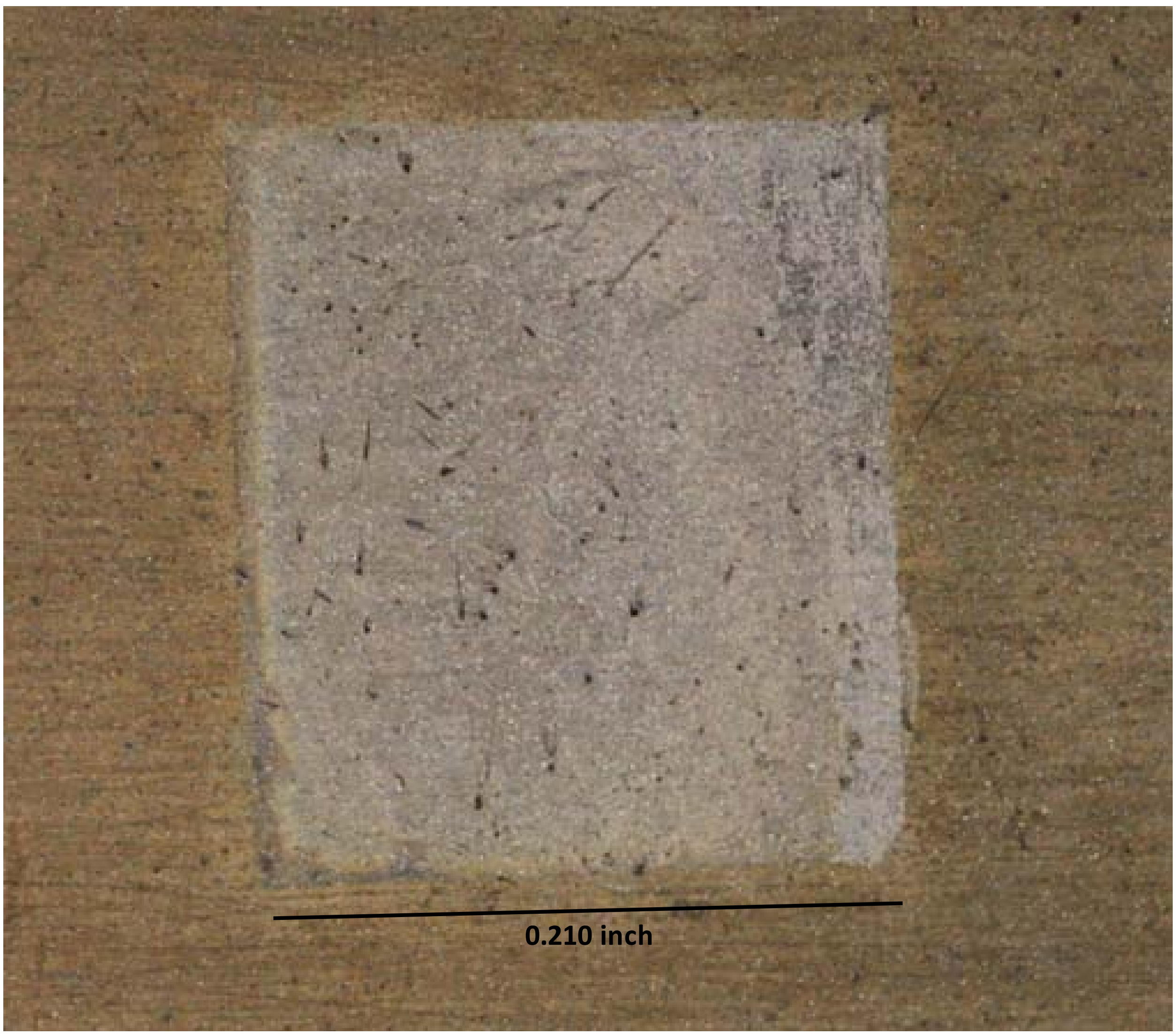


Figure 16. Close-up Picture of the Center of 2024-T3 Specimen 601-14

10.5 Analytical Analysis

Microscope-based (μFTIR) analysis of scrapings from the surface of a specimen blank stripped with PMB-V provided strong spectra that indicated material composed of polymethyl methacrylate, typical of Type V plastic media. Spectra obtained from μFTIR analysis of material collected from a specimen blank stripped with PMB-II confirmed the presence of urea-formaldehyde type resins, typical of Type II plastic media. However, the latter spectra exhibited relatively weak absorptions corresponding to very small quantity of Type II media residue. No organic materials were detected in material collected from the polished, untreated surfaces of the specimen blanks.

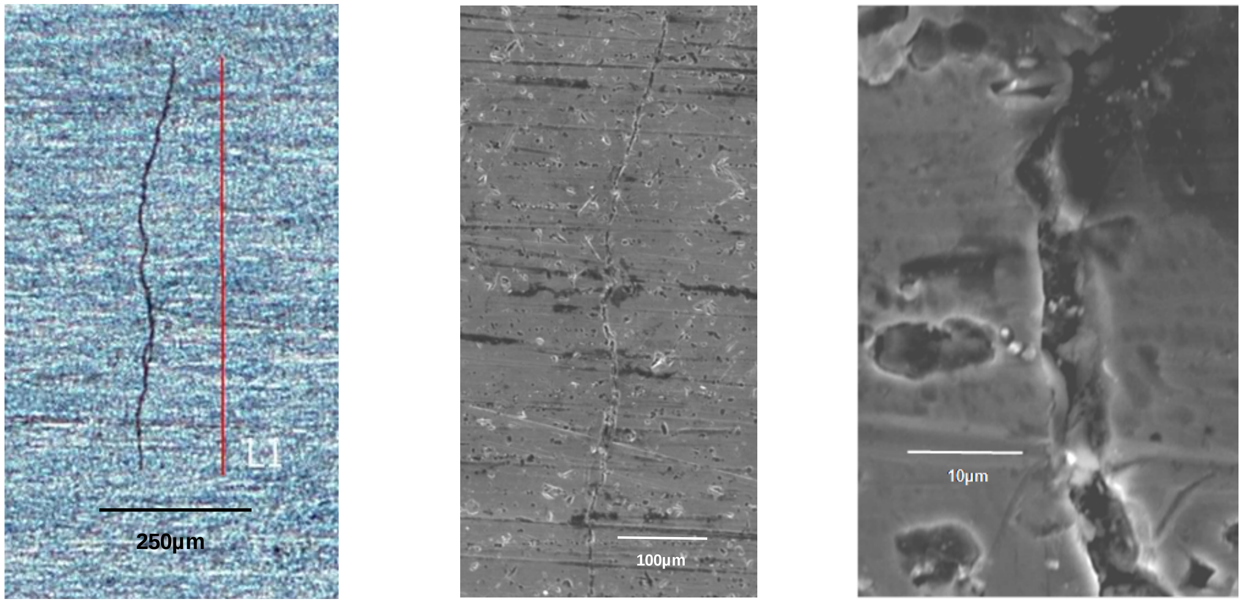
The X-ray Fluorescence (XRF) analysis indicated elevated levels of chromium on the surfaces of specimen blanks that had been painted and stripped. This was probably due to the chromate conversion coating (alodine) that was applied prior to painting. Analysis of material collected from the polished, untreated surfaces of specimen blanks revealed only compositions typical of the two aluminum alloys from which the cracked specimens were made.

10.6 Microscopic Examination

10.6.1 Specimens Stripped with PMB-II

Post-strip microscopic examination of specimens stripped with PMB-II revealed evidence of metal upset/peening on the specimen surfaces due to media impingement, media embedded in a crack and reduced crack-openings. These findings correlated with the significant reductions in FPI indication brightnesses discussed in Section 10.1 and pictured in the Appendix.

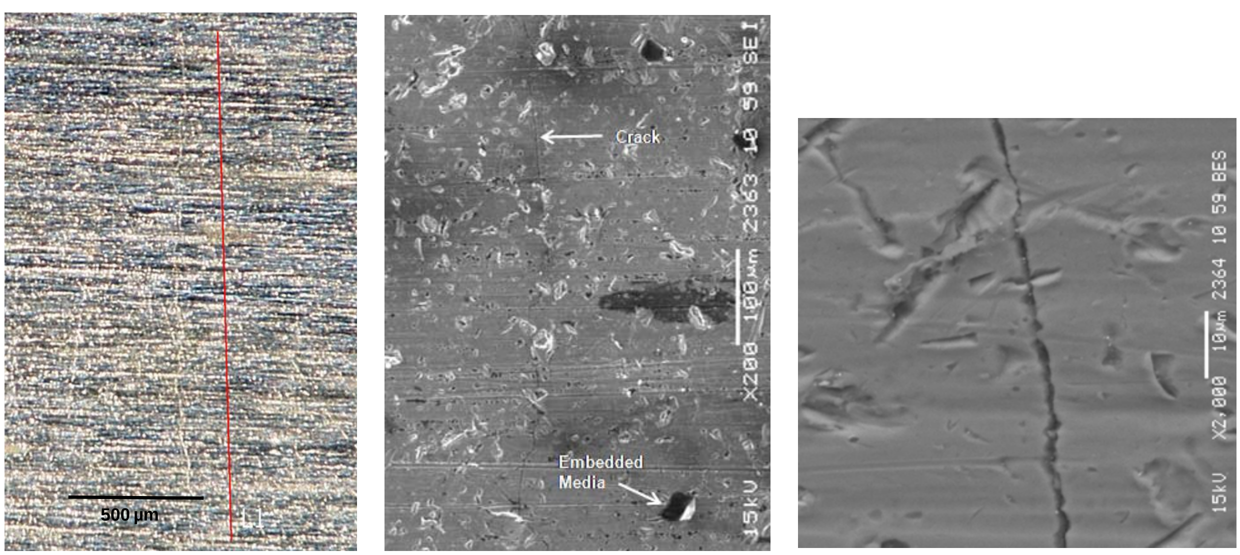
Figure 17a is an image of the crack in 7075-T6 specimen 609-04 before painting. The red line in the figure is the crack-length measurement indicator. The crack measured 0.028 inch long and produced a dim (3.1 fL) but detectable pre-paint indication (Figure A-2a). Figure 17b is a post-strip SEM image showing part of the crack; in the un-cropped image the entire crack was visible. After paint removal the crack produced a very dim (0.4 fL), barely detectable FPI indication (Figure A-2a). A higher magnification SEM image in Figure 17c shows foreign material inside the crack that contributed to the degraded FPI indication. Energy dispersive spectroscopy revealed that the foreign material had high carbon content, consistent with plastic media chemistry.



(a) Pre-Paint Optical Image
(b) Post-Strip SEM Image of Part of the Crack
(c) High Magnification SEM Post-Strip Image of the Crack

Figure 17. Images of the Crack in 7075-T6 Specimen 609-04

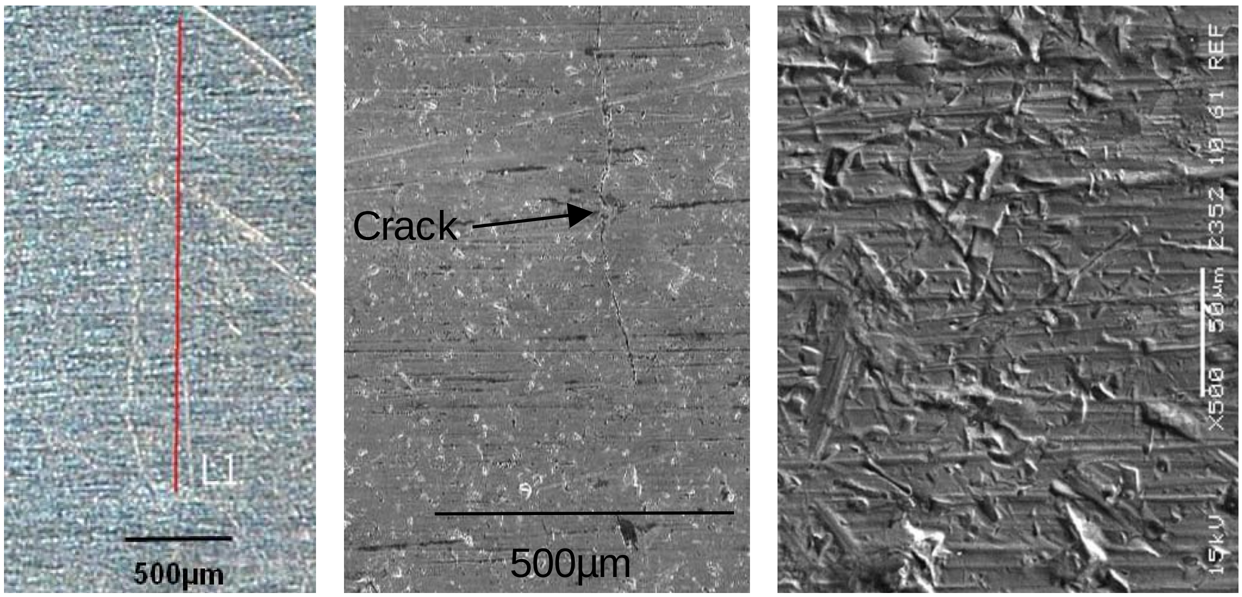
Microscopic examination of 7075-T6 specimen 609-05 revealed a long (0.074 inch) and tight crack (Figure 18a), but one that produced a good pre-paint FPI indication (Figure A-2b). The post-strip image in Figure 18b provides a good view of different surface features: 1) media impingement on the specimen surface with little metal upset (small dark spots), 2) metal upset (brighter irregular marks) occasionally bridging the crack and 3) embedded media (large sharp-cornered irregular dark areas). The more highly magnified post-strip image in Figure 18c shows small amounts of media embedded in the crack and metal smear closing part of the crack opening. The post-strip FPI indication (Figure A-2b) was barely visible.



(a) Pre-Paint Optical Image
(b) Post-Strip SEM Image
(c) High Magnification Image

Figure 18. Post-Strip Image of Crack in 7075-T6 Specimen 609-05

Figure 19a is a pre-paint optical image of the crack in 2042-T3 specimen 601-06. The 0.088-inch crack produced a bright (120 fL) pre-paint FPI indication (Figure A-7c). Figure 19b is a post-strip SEM image of the only visible part (0.028 inch) of the crack. Although the crack is narrow, it is quite visible in this magnified image. However, no FPI indication was obtained after paint removal. Careful examination revealed that the crack opening was intermittent. The more highly magnified image in Figure 19c shows the surface topography where the crack should have been, beyond one end of the partial crack shown in Figure 19b.



(a) Pre-Paint Optical Microscope Crack Image

(b) Post-Strip SEM Image of the Visible Part of the Crack

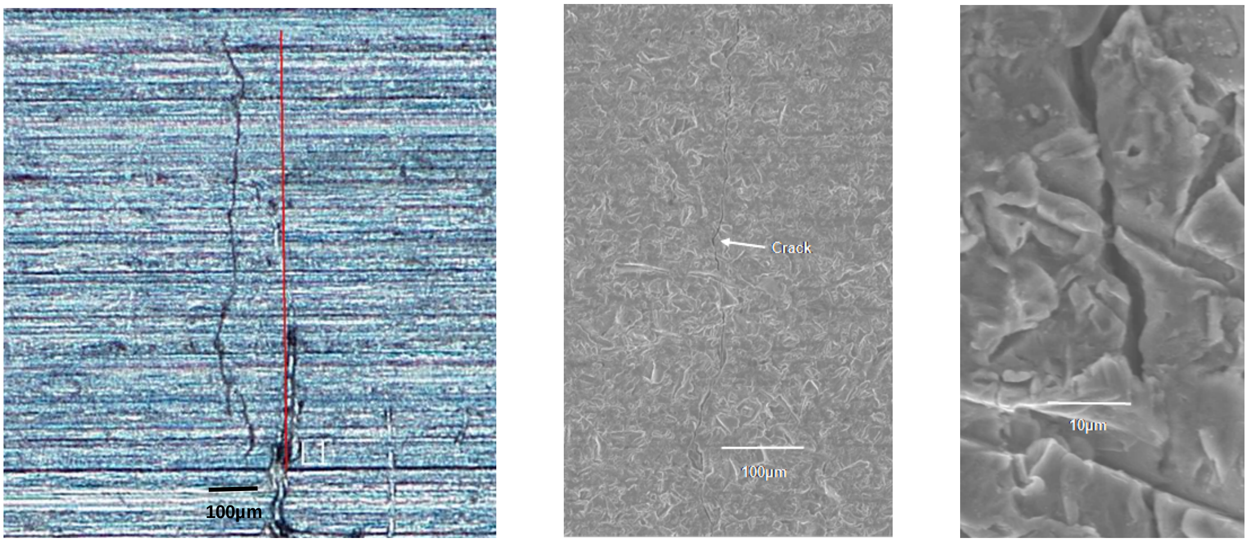
(c) Post-Strip SEM Image of an Area where PMB-II Obscured the Crack

Figure 19. Images of the Crack in 2024-T3 Specimen 601-06

10.6.2 Specimens Stripped with PMB-V

Post-strip microscopic examination of specimens stripped with PMB-V provided images of completely different surface topography compared to that of specimens stripped with PMB-II. What appeared in the images to be a significantly disturbed surface on the specimens stripped with PMB-V was actually the residual coating of the Type V media, which also was embed inside cracks. Although the Type V media is softer, evidence of craters surrounded by erupted metal was discovered when a specimen surface was lightly sanded with a 600-grit paper to remove the residual coating.

Figure 20 contains microscope images of 7075-T6 specimen 609-14. The small crack (0.035 inch) produced a barely detectable (3.1 fL) pre-paint FPI indication and an even dimmer (0.1fL) and shorter post-strip indication (Figure A-3c). A reason for the indication degradation can be seen in the post-strip SEM images shown in Figure 20b and Figure 20c: the crack is nearly obscured by the PMB-V residue, which has an extremely uneven topography that gives the surface the appearance of being significantly disturbed. In addition the machining grooves seen in Figure 20a are obscured with the PMB-V in the post-strip images. On the other hand, in similar images of specimens shown in above in Section 10.6.1 the machining marks are still visible in post-strip images of specimens stripped with PMB-II.



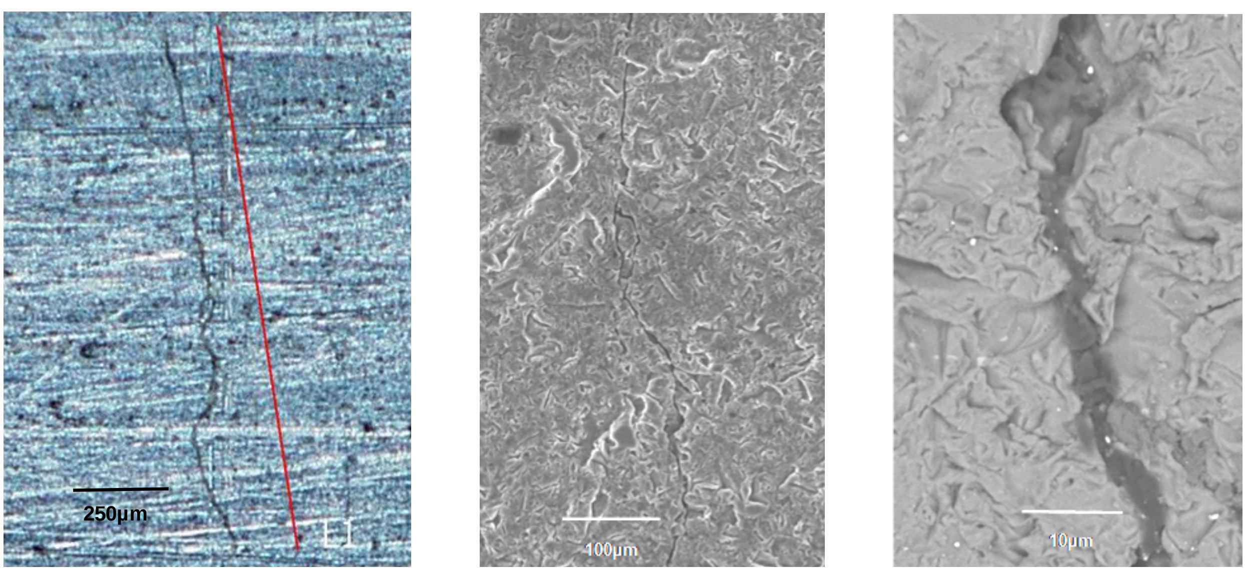
(a) Pre-Paint Optical Microscope Image

(b) Post-Strip SEM Image of Nearly Obscured Crack

(c) Part of Crack in (b) at Higher Magnification

Figure 20. Images of the Crack in 7075-T6 Specimen 609-14

Figure 21 contains microscope images of 2024-T-3 specimen 601-15. The crack was 0.054 inch long and produced a good (46 fL) pre-paint FPI indication (Figure A-8b). However, it produced no post-strip indication. One reason is the significant amount of media entrapped in the crack, shown in Figure 21c. The extremely uneven topography of the coating is again evident in both Figure 21b and Figure 21c. The coating was also visible on a mounted cross-section of a specimen blank as an additional distinct layer on the half that had been painted and stripped with PMB-V.



(a) Pre-Paint Optical Image

(b) Post-Strip SEM Image of Crack

(c) Post-Strip Image of Coating Material in Crack

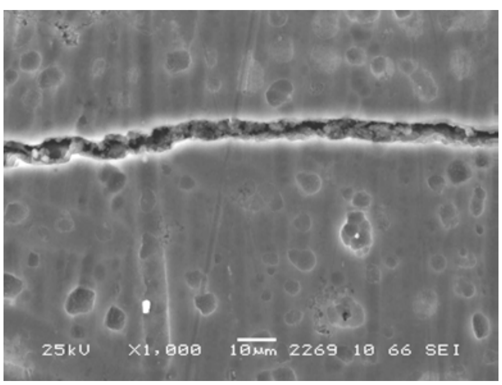
Figure 21. Images of the Crack in 2024-T3 Specimen 601-15

10.6.3 Specimens Stripped with Chemical Stripper

SEM examination of one of the specimens processed with chemical stripper unexpectedly revealed that the crack was filled with stripper and dissolved paint residues. This explained the surprisingly poor post-strip FPI results for chemical stripper. Chemical stripper had been chosen as one of the paint-removal media because it was expected to be the "reference" paint stripping process, i.e., least detrimental to the FPI indications. However, that did not prove to be the case.

Specimen 609-03 was selected for microscopic examination because of all specimens treated with chemical stripper it had produced the brightest pre-paint indication (71.4 fL) even though it was the shortest crack (0.024 inch) in either chemical group. Figure 22 shows two images of the crack at different magnifications. Spectroscopy measurements of the material in the crack showed relatively high amounts of carbon and oxygen indicative of stripper, and silicon, titanium and calcium indicative of paint. Although no scraping or other mechanical means was used to remove the softened paint, the solvent flowed into the crack taking with it dissolved residue. The mechanical action of the rinse water used to remove the softened paint from the specimen surface was not effective in removing residue from the crack, so the stripper solvent volatized and the re-solidified residue remained. Subsequent ultrasonic cleaning of specimens immersed in more of the chemical stripper or other solvents (acetone and methyl ethyl ketone) could not remove the residue, as verified with SEM examination and unsuccessful FPI.

The rounded dimples in the Figure 22 images are typical of a surface that has been etched. Mild etching was typically used on specimens to eliminate any smeared metal remaining from machining that was performed to remove evidence of the slot used to initiate crack growth.



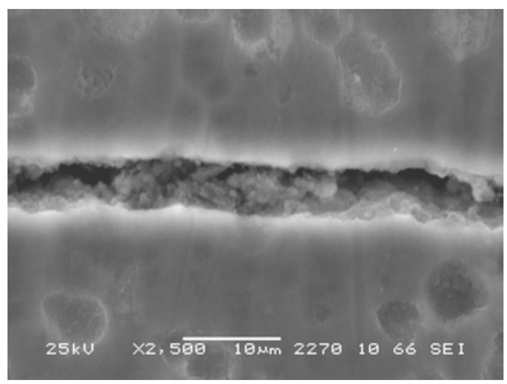


Figure 22. Post-Strip Images of the Crack in 7075-T6 Specimen 609-03

10.6.4 Specimens Stripped with Atmospheric Plasma

Microscopic examination of the specimens stripped with plasma produced more information about the unexpected surface features first noted with the low magnification visual examination. The three features were unique to the atmospheric plasma process. First were the irregular dark spots that became brighter with higher magnification and took on the appearance of minor surface erosion. Second were the bright circular dots that under the microscope appeared to be re-solidified pools of melted aluminum. Finally, the small black dots seen at low magnification appeared to be shiny, black deposits of splattered molten material that had a nearly circular shape or an oblong shape with a tail depending on whether the material hit the surface perpendicularly or at an angle.

The first two features were intermixed with numerical density of up to approximately 100 per mm^2. The size of the irregular spots ranged up to approximately 100 µm although sometimes they were chained together and difficult to measure individually. The sizes of the bright circular spots ranged from 1 to 25 µm. The black splatter was randomly located and up to 200 µm long. None of these features severely affect the FPI indications. In fact, as discussed in Section 10.1 and shown in Figure **A-5** and Figure A-10, the majority of the indications in the plasma-stripped groups improved.

According to AP Solutions it is possible that the irregular and circular spots are the result of micro-arcs that occurred between the plasma and the aluminum. The black splatter could be copper eroded from the nozzle/electrode. The full effects of these features on metallurgical properties of the alloys and NDI results are not fully understood at this point, and more evaluation needs to be made of this new paint-removal process. AP Solutions is beginning to look into these surface phenomena as part of a Small Business Innovative Research project sponsored by AFRL.

The following figures depict various combinations of the plasma-induced surface phenomena. Figure 23 shows all three types.

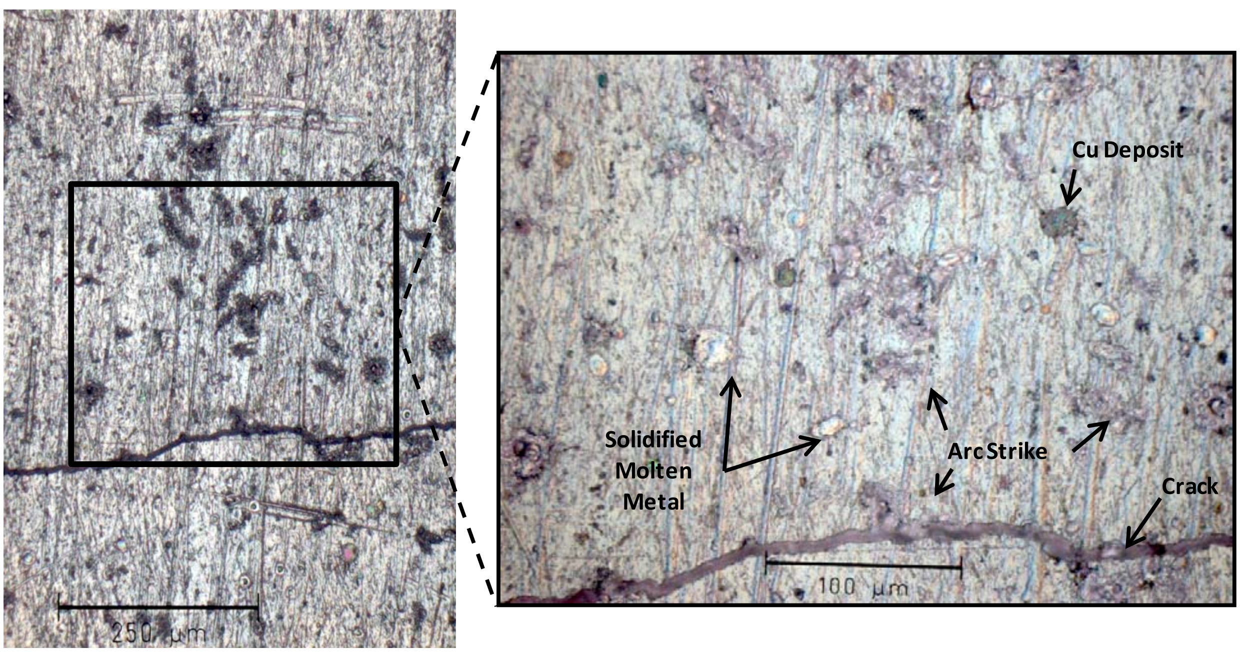


Figure 23. Surface Phenomena Produced by Plasma Stripping on 609-08

Figure 24 shows arc strikes on 901-21, around and over the crack. The latter did not affect the post-strip FPI indication, which was slightly brighter than the pre-paint indication (Figure A-10d).

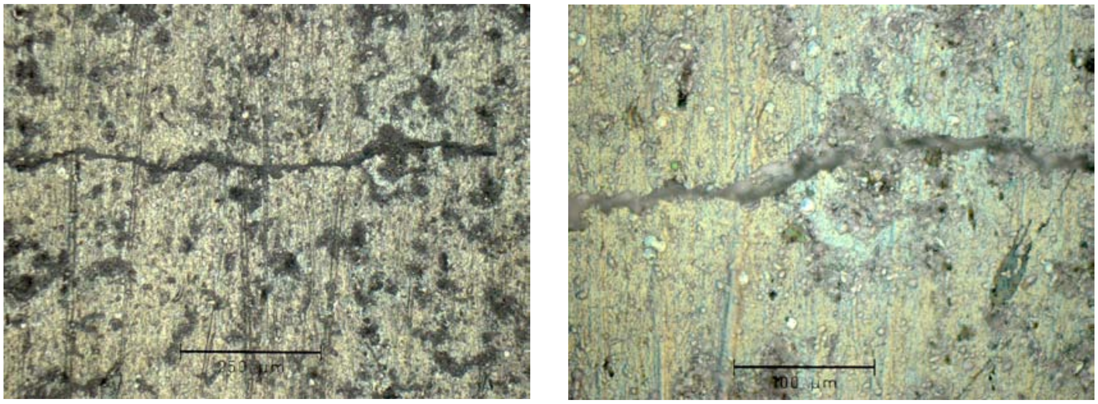
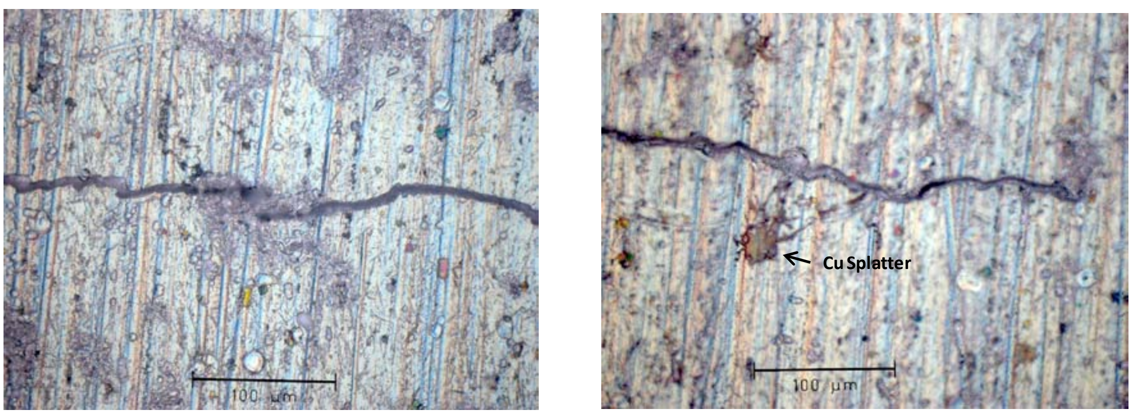


Figure 24. Arc Strikes Surrounding and on Top of the Crack in 601-21

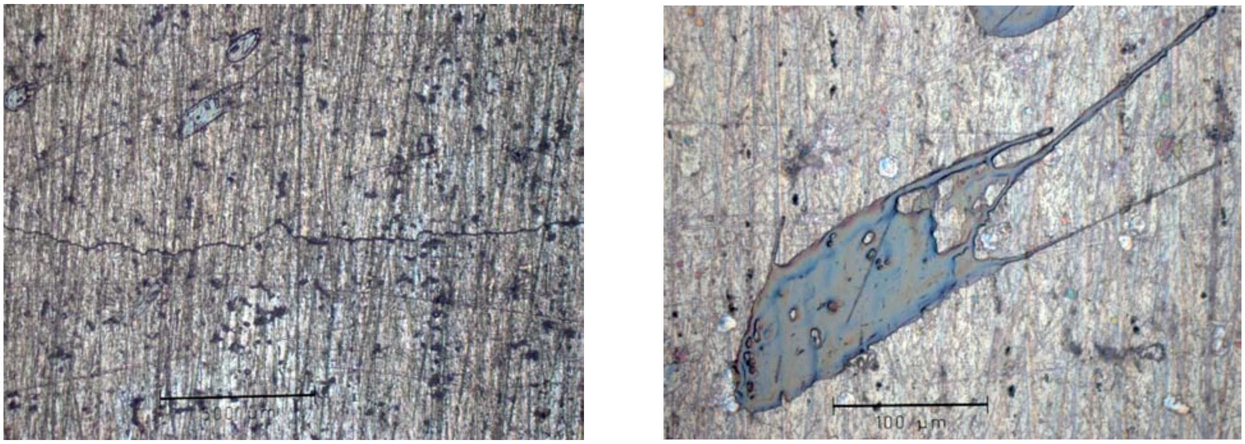
Figure 25a shows an arc strike on the crack in 609-10 and Figure 25b shows foreign material inside the crack. The post-strip degradation of the FPI indication (Figure A-5c) could have been caused by either or both of these phenomena. The copper splatter just below the filled part of the crack in Figure 25b could also have adversely affected an FPI indication if it had landed directly on the crack.



a) Arc Strike on Crack b) Foreign Material inside Crack

Figure 25. Surface Phenomena on 609-10 Produced by Plasma Stripping

Figure 26a shows three directional copper splatters in the upper left corner. An enlarged view of the largest is shown in Figure 26b.



(a) Angled Copper Splatter (b) Close-up of Large Splatter in (a)

Figure 26. Angled Copper Splatter on Specimen 601-08

Figure 27 shows two views of the shiny round spots on 601-08 at different magnifications.

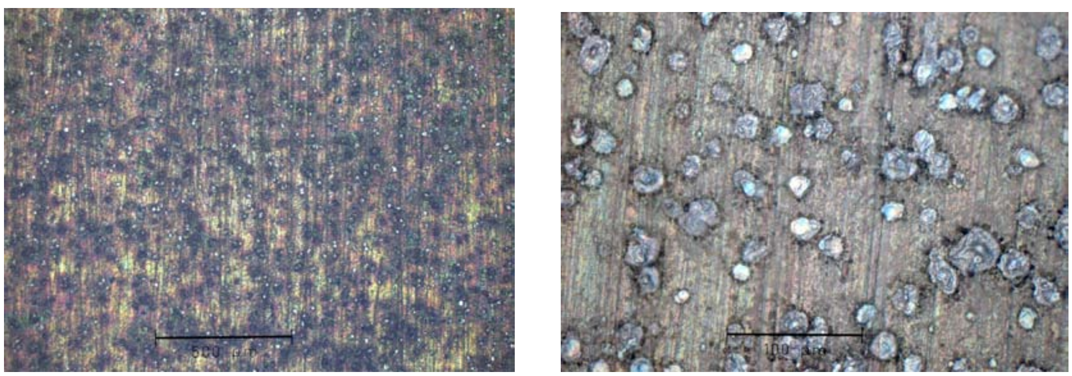


Figure 27. Circular Shiny Spots Produced by Plasma Stripping of 601-08

11. CONCLUSIONS

Of the four media used for stripping paint only atmospheric plasma did not cause significant numbers of FPI indications to become virtually undetectable. Only one crack had an indication of questionable detectability, and it was a very small crack (0.024 inch) that had low, yet detectable, pre-paint brightness. There were small cracks in other media groups that didn't retain their pre-paint brightnesses either, but bright indications of larger cracks in the PMB and chemical-strip groups did not survive stripping well enough to consider FPI a reliable NDI technique to use after stripping with those media.

Post-strip microscopic examination of specimens stripped with Type II plastic media confirmed expectations of metal upset on the specimen surfaces due to media impingement, media embedded in cracks and reduced crack-openings, all of which correlated with the significant reductions in pre-paint FPI indication brightnesses.

Type V media provided no improvement as a pre-FPI stripping method over Type II when trying to avoid severe degradation of FPI crack indications. Although the Type V media is softer, evidence of peening was discovered on specimen surfaces. Furthermore, the media residue on treated specimen surfaces and inside cracks added another impediment to reliable FPI.

Widely used chemical paint stripper is not as innocuous as presumed. Residues of stripper and dissolved paint inside a crack proved the chemical-strip process to be as culpable as plastic media blasting for severe degradation FPI crack indications.

Cold atmospheric pressure air plasma is a promising paint-stripping process because it was the least detrimental to FPI crack indications. However, the application of this new process needs to be refined, and the physical and metallurgical effects of the surface contamination that results from the process need more study.

Eddy current inspection is a viable technique for detecting cracks in 7075-T6 and 2024-T3 after removing paint with plastic media blasting, chemical stripper or atmospheric plasma. The lower post-strip amplitudes for the PMB-V group may be due to additional probe lift-off caused by the residual coating. The presence of the alodine coating may have influenced the post-strip signal measurements, even though precautions were taken to minimize additional probe lift-off during post-strip measurements. Since more of the alodine coating appeared to have been removed with the PMB-II, that condition may have provided the relatively higher post-strip signals for those groups. Nevertheless, the failure to precisely duplicate the pre-paint calibration procedure for the post-strip inspection is still a possibility. The variability inherent in a manual eddy current inspection undoubtedly contributed to the signal changes also.

None of the paint-stripping processes had a significant effect on either the bulk or superficial hardness of the 7075-T6 or 2024-T3 specimens. Remaining alodine coating did not affect the hardness readings because the coating is very soft by nature. The only trend warranting further study was decrease in hardness of the specimens stripped with plasma. In particular, decreases in bulk hardness approaching five percent should be evaluated further because of the five-percent limit on process-induced hardness decreases imposed by material specifications.

12. RECOMMENDATIONS

The use of plastic media blasting to remove paint from aluminum alloys prior to fluorescent penetrant inspection needs to be revisited.

The widely used chemical stripping process should be evaluated further. A comparison should be made between the chemical strip technique used in this study and the techniques used in the USAF maintenance venues to see if the former was a realistic representation of the latter.

Development of the atmospheric plasma organic-coating removal process should continue, specifically as it applies to aluminum structures used by the USAF.

Other paint-stripping media should be evaluated, e.g., CO_2 pellets, plant-seed hulls.

Other NDI technology (e.g., wide-field eddy current, sonic infrared) should be evaluated as an alternative to FPI.

APPENDIX

List of Appendix Figures

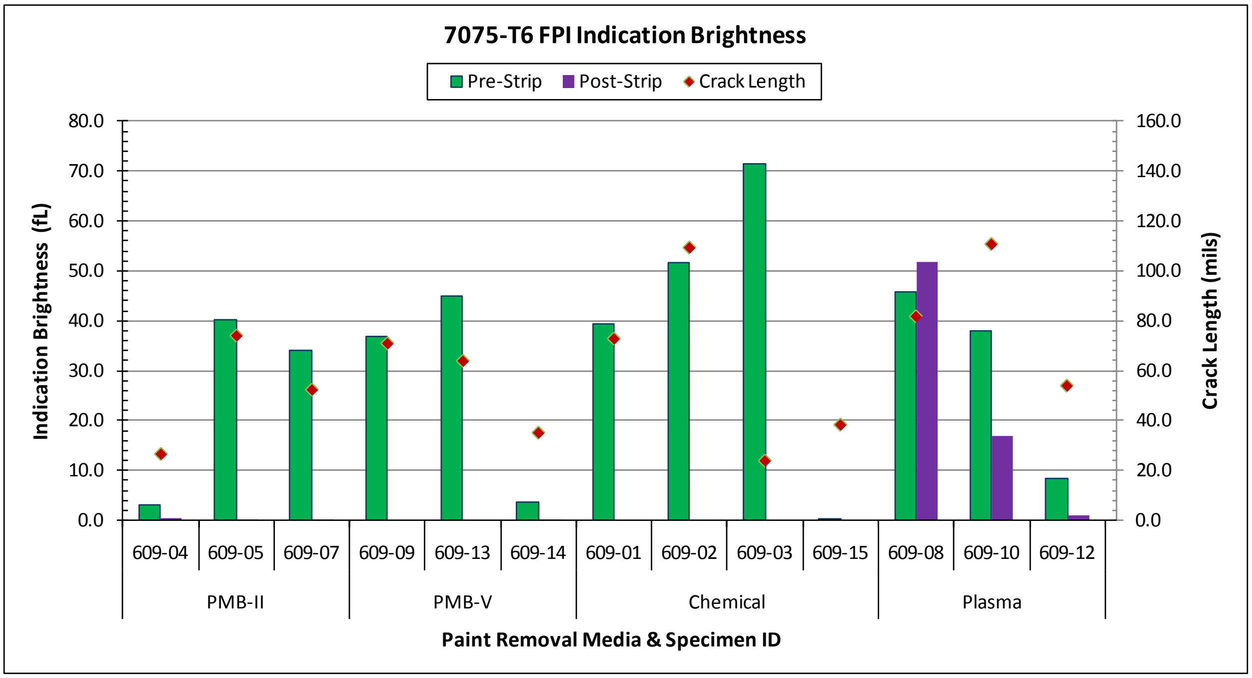


Figure A- 1. FPI Data and Crack Lengths for 7075-T6 Specimens

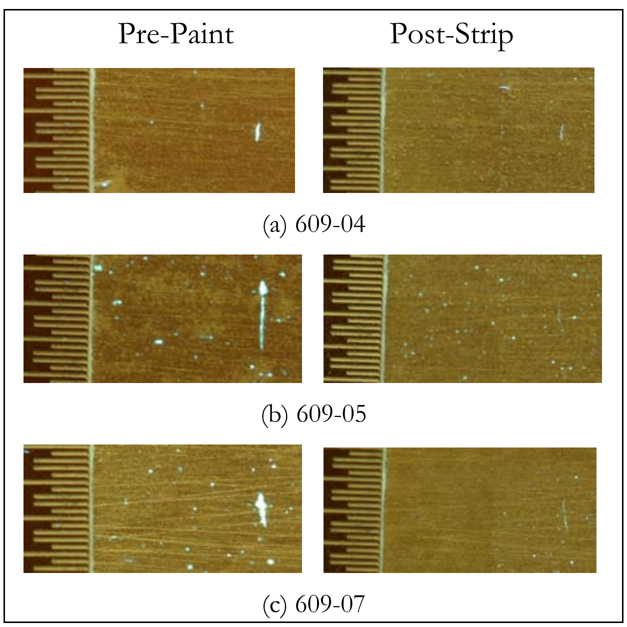


Figure A-2. FPI Indications for 7075-T6 Specimens Stripped with PMB Type II

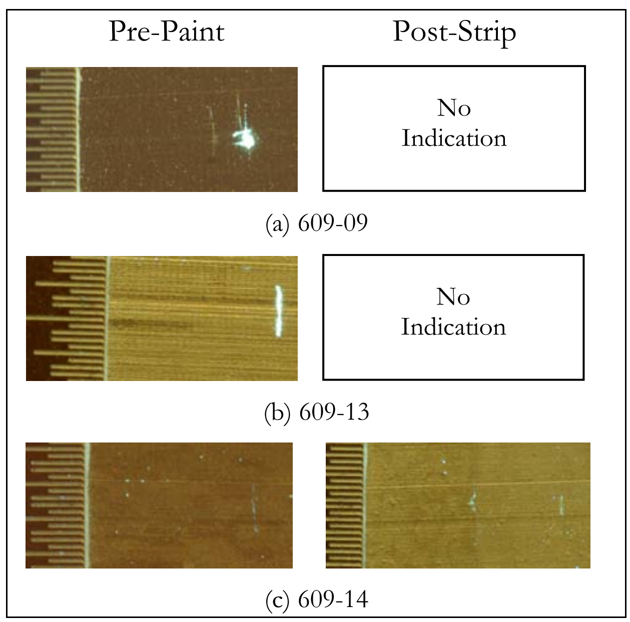


Figure A-3. FPI Indications for 7075-T6 Specimens Stripped with PMB Type V

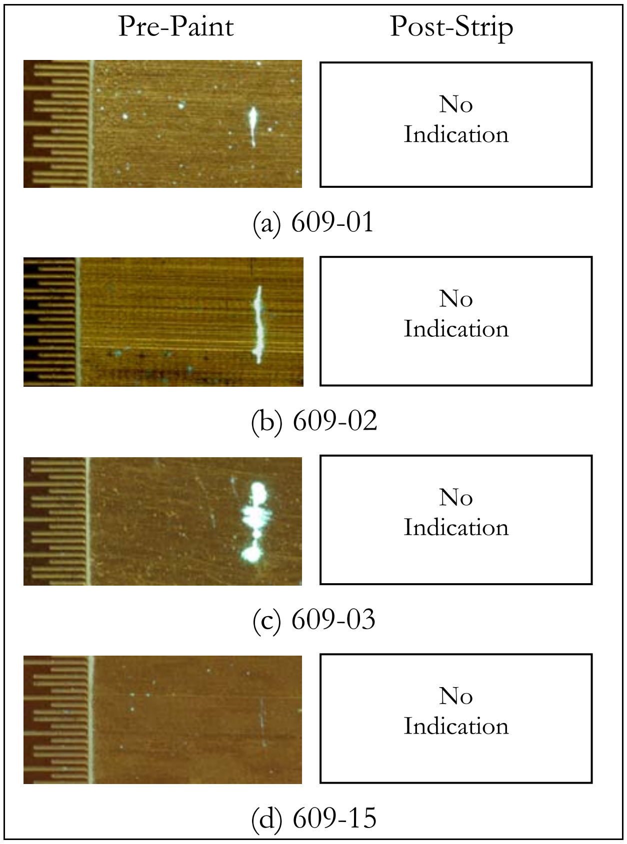


Figure A-4. FPI Indications for 7075-T6 Specimens Stripped with Chemicals

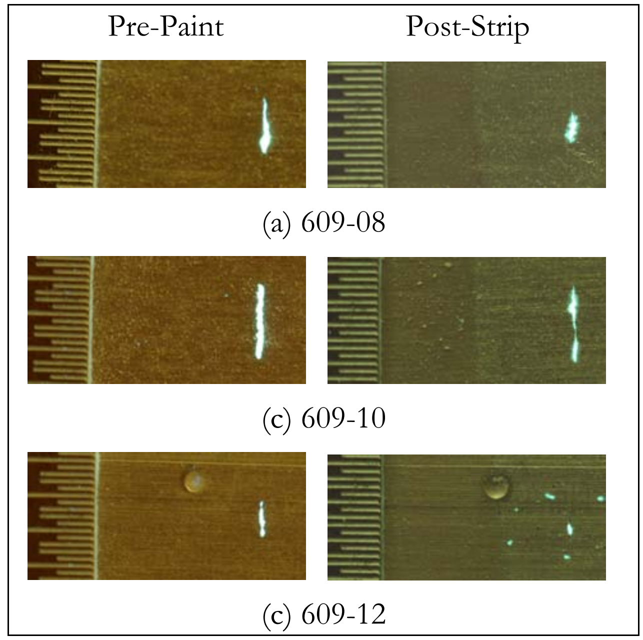


Figure A-5. FPI Indications for 7075-T6 Specimens Stripped with Plasma

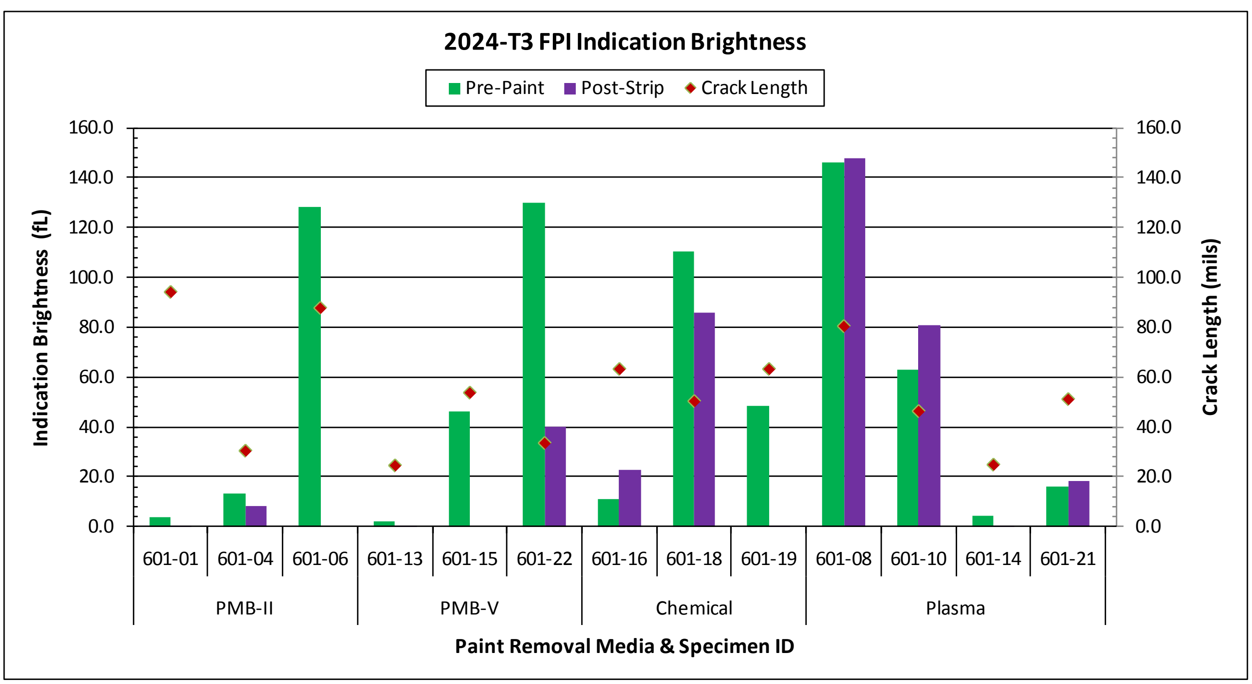


Figure A- 6. FPI Data and Crack Lengths for 2024-T3 Specimens

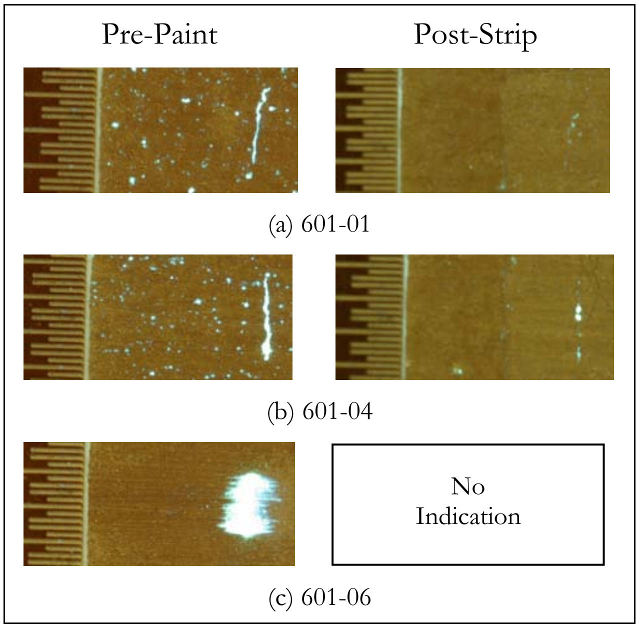


Figure A-7. FPI Indications for 2024-T3 Specimens Stripped with PMB (Type II)

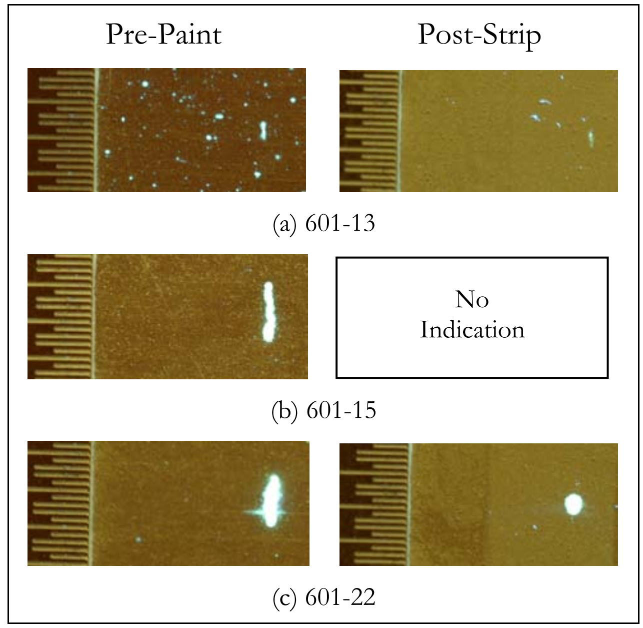


Figure A-8. FPI Indications for 2024-T3 Specimens Stripped with PMB (Type V)

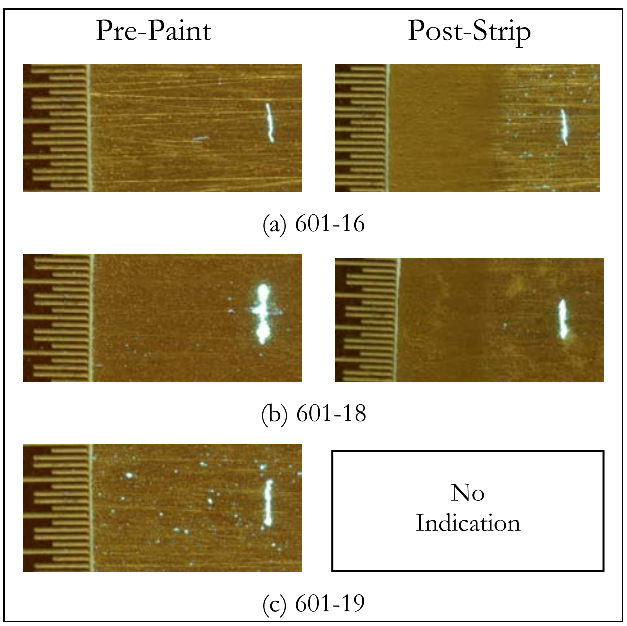


Figure A-9. FPI Indications for 2024-T3 Specimens Stripped with Chemicals

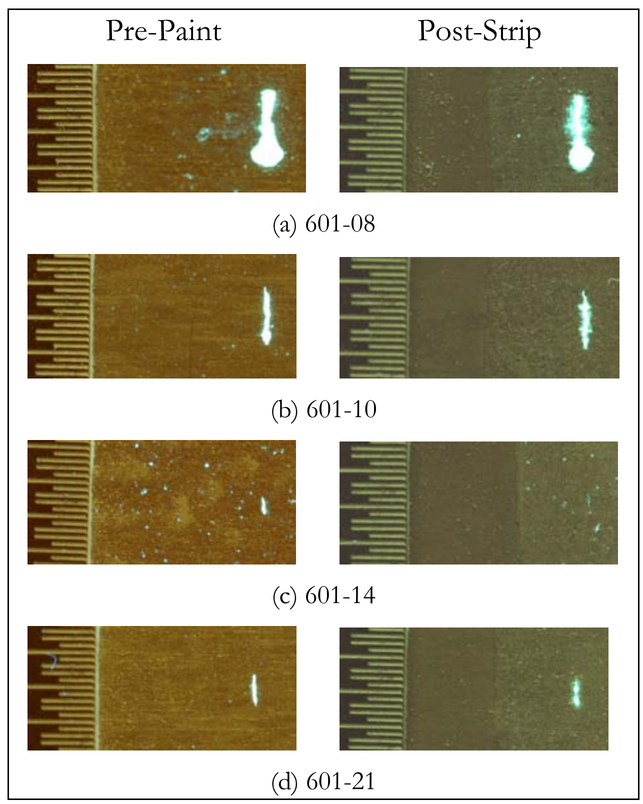


Figure A-10. FPI Indications for 2024-T3 Specimens Stripped with Plasma

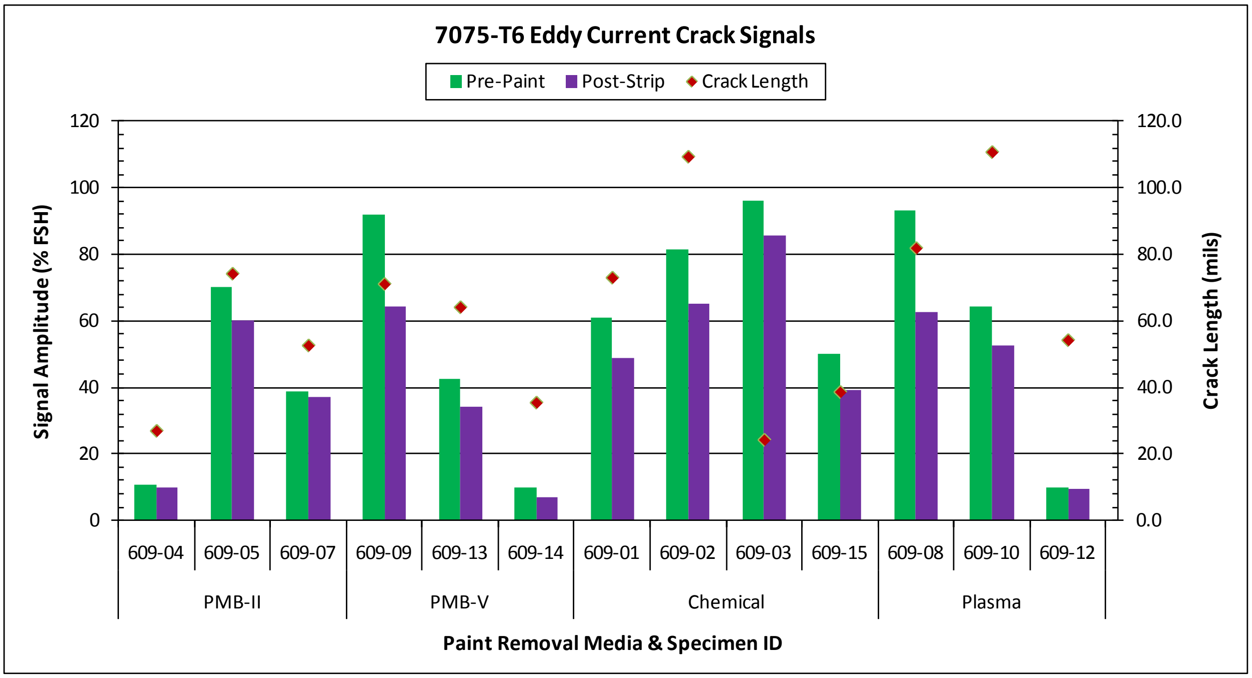


Figure A-11. Pre-Paint and Post-Strip Eddy Current Crack Responses for 7075-T6

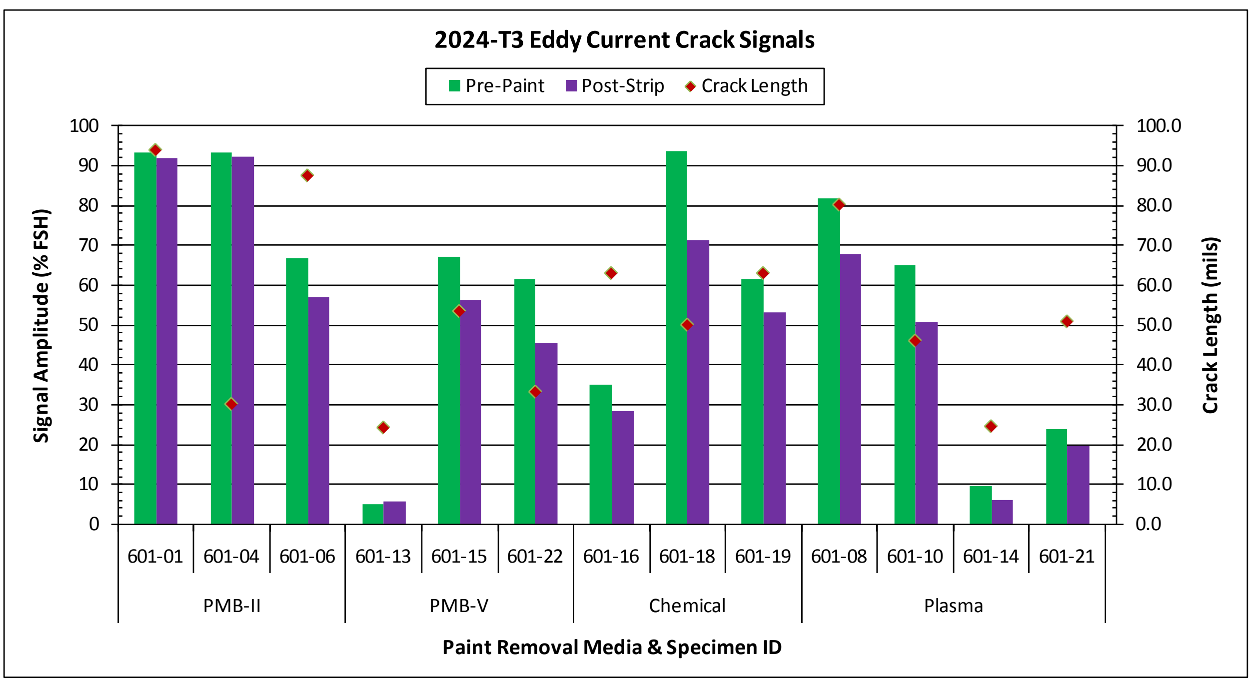


Figure A-12. Pre-Paint and Post-Strip Eddy Current Crack Responses for 2024-T3

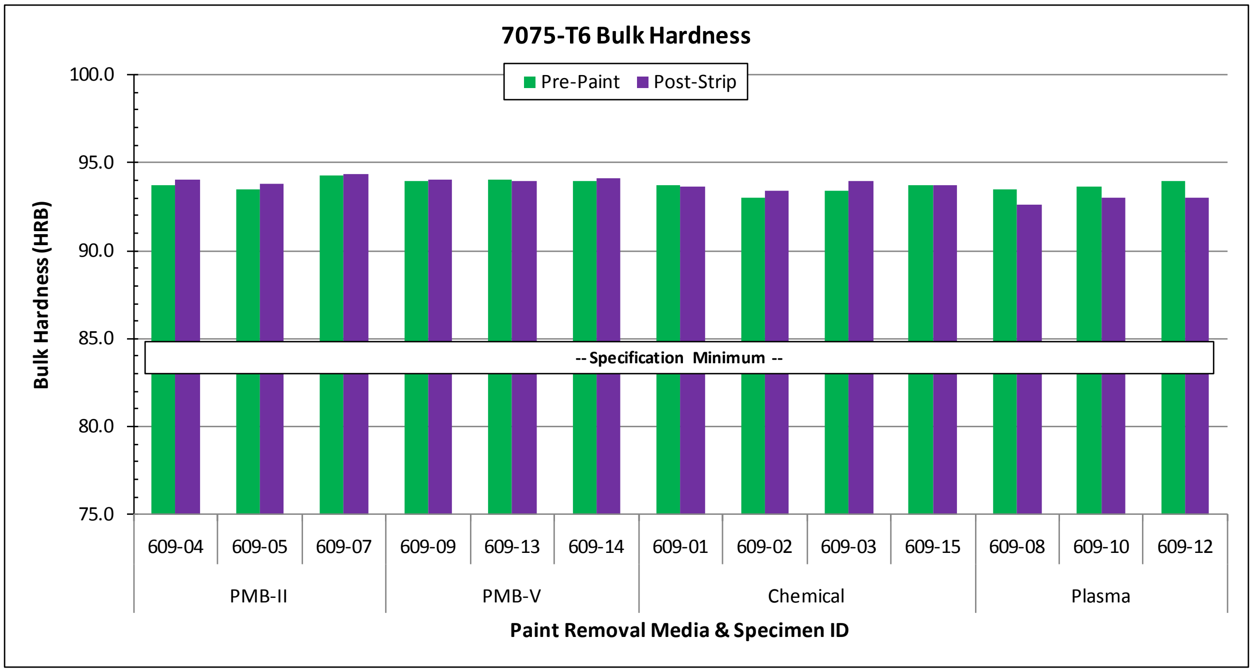


Figure A-13. Bulk Hardness Measurements on 7075-T6 Specimens

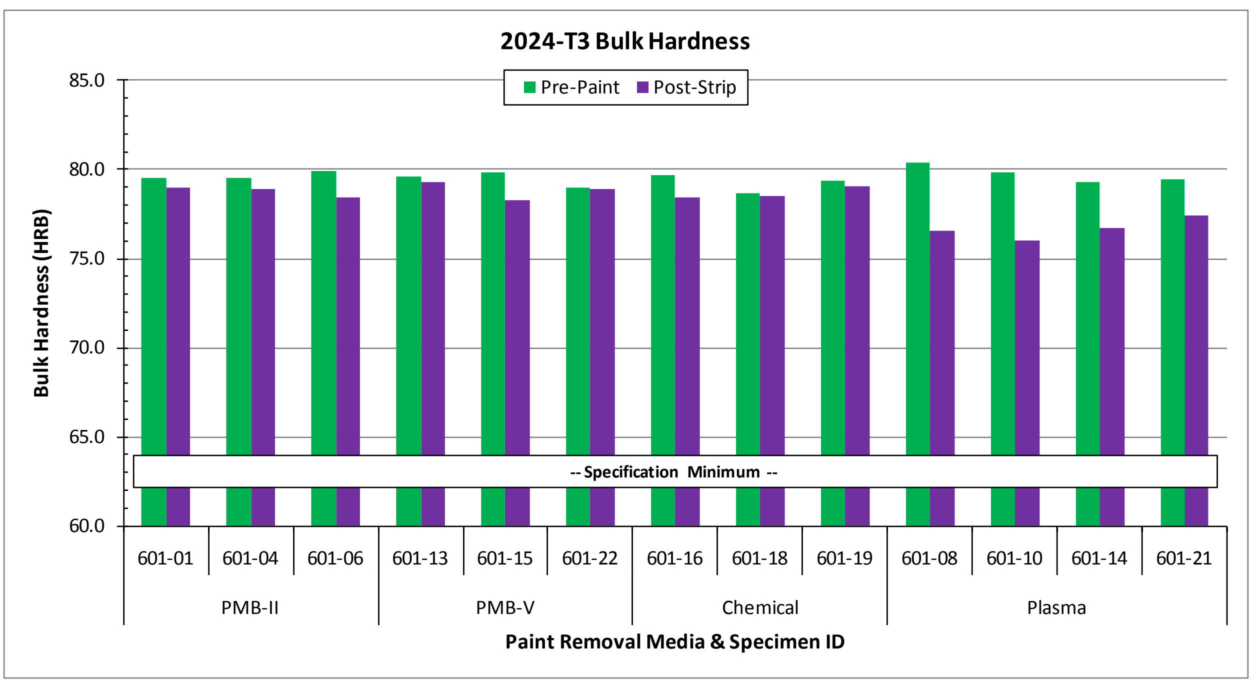


Figure A-14. Bulk Hardness Measurements on 2024-T3 Specimens

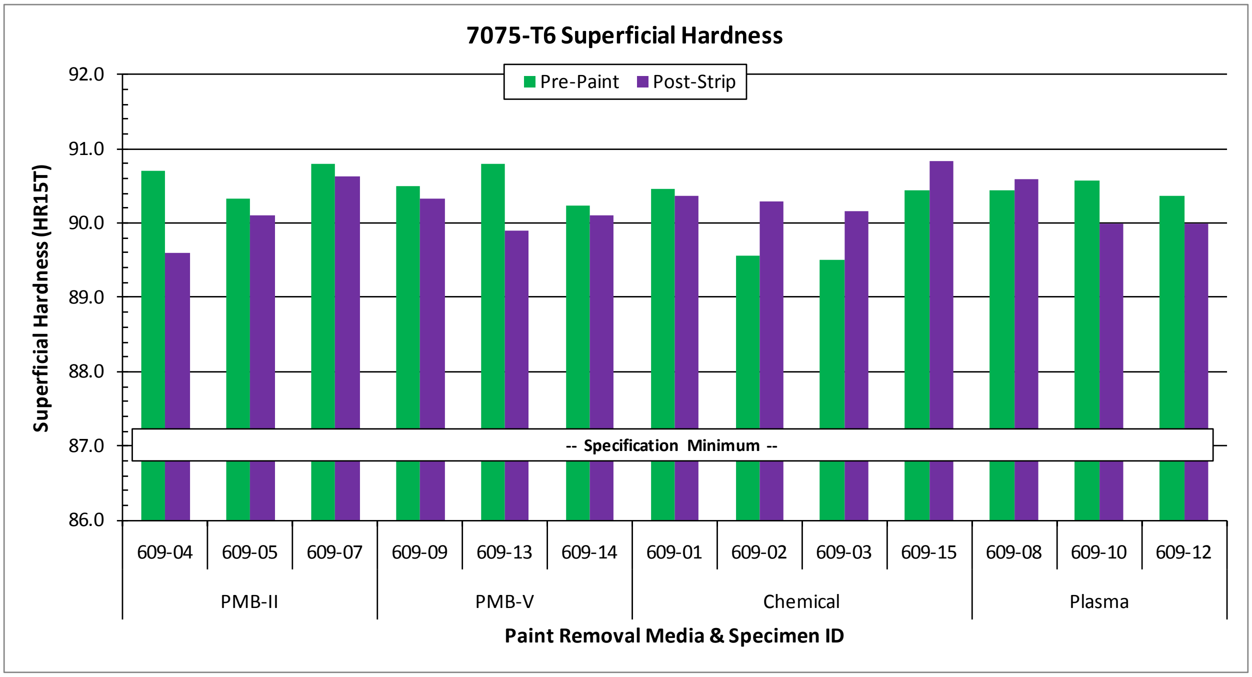


Figure A-15. Superficial Hardness Measurements on 7075-T6 Specimens

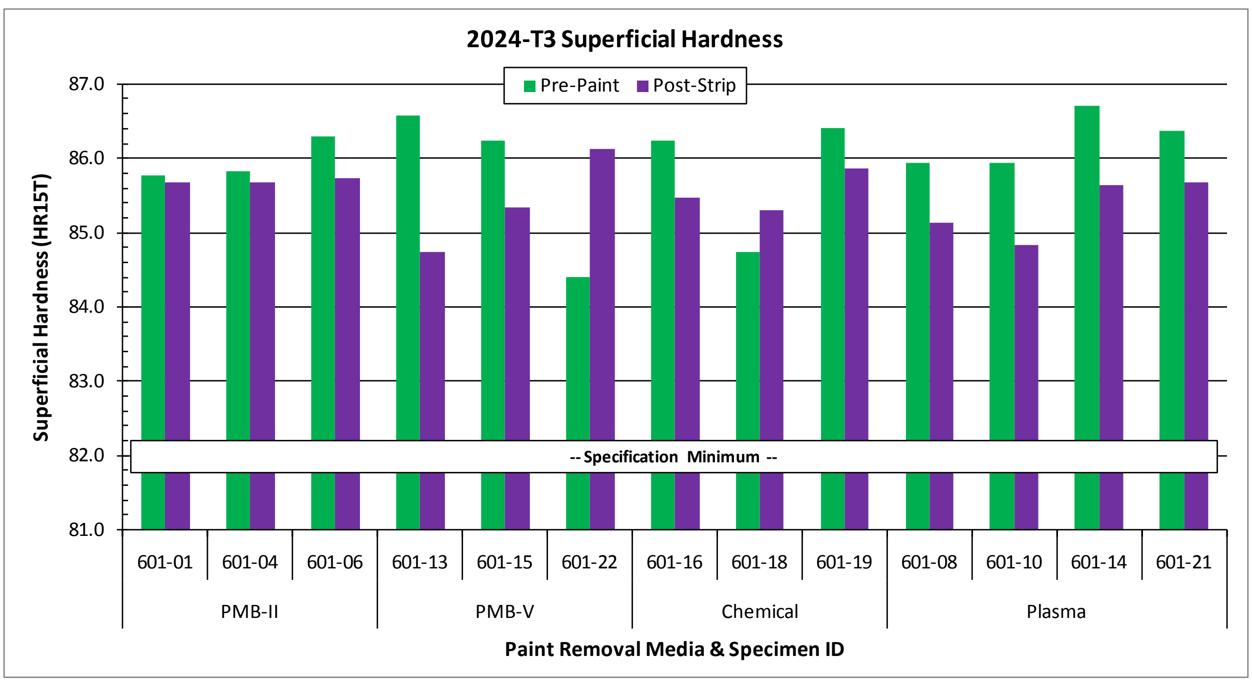


Figure A-16. Superficial Hardness Measurements on 2024-T3 Specimens